

Eureka

Conversations About The Atomic Nucleus

Vera Chernogorova



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After graduating from the Faculty of Physics and Mathematics at university, Vera Aleksandrovna entered postgraduate studies and later became a research fellow at the Joint Institute for Nuclear Research in the town of Dubna.

For nearly twelve years, she participated in experiments conducted on a particle accelerator – the synchrocyclotron.

Vera Aleksandrovna is a co-author of many scientific papers on the study of the properties of mu-mesons.

In recent years, she has published over ten articles in journals such as *Znanie – Sila* (Knowledge Is Power), *Science and Life*, *Technology for the Youth*, and others.

The topics of these articles include problems in nuclear physics, high-energy physics, astrophysics, controlled thermonuclear fusion, the application of scientific achievements in human practice, and the future of science. Many of these articles have been reprinted in foreign journals.

In 1973, our publishing house released her book *Mysteries of the Microworld*, which discussed some current problems in the physics of elementary particles. *Conversations About the Atomic Nucleus* is the author's second book to appear in the Eureka series.

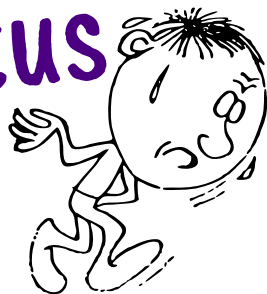
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CONVERSATIONS

ABOUT THE

ATOMIC NUCLEUS



Vera Chernogorova

Translated from the Russian by
Damitr Mazanav

The Mir Titles Project 2025

Vera Aleksandrovna Chernogorova

Conversations About The Atomic Nucleus

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Illustrations: *K. Moshkin*

Translated from the Russian & typeset in $\text{\LaTeX}$ by *Damitr Mazanav*

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Annotation

The book discusses issues related to the study of the atomic nucleus and its structure, nuclear forces, and the components of the nucleus. It also describes the achievements of Soviet scientists in the field of nuclear energy.

Translator's Note

This is the second book by Vera Chernogorova in the *Eureka* series that I am translating.

Like in the earlier book by Vera Chernogorova , *Mysteries of the Microworld*,¹ I have added a Postface which summarises some of the major achievements and trends in the fields of nuclear and plasma physics. Mistakes and omissions (and I am sure they will be there), if any, are my own.

¹ The book can be accessed [here](#).

Damitr Mazanav
damitr@proton.me

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FROM ATOM TO THE NUCLEUS



1 From Atom to Nucleus

- The word “*atom*” appears quite often in newspapers, magazines, and books, is spoken on radio and television broadcasts, and we have grown accustomed to it. But we hear about the atomic nucleus far less frequently. Perhaps this part of the atom is insignificant and only of interest to specialists?
- Not at all! In cases where people speak of *atomic energy* or *atomic power stations*, you can be sure they actually mean nuclear energy and nuclear power stations.
- And when a poet calls our age the *atomic age* — is that a slip of the tongue or just because lyricists do not know physics?
- Not quite. The unpopularity of the atomic nucleus reflects a certain objective fact.

The cradle of nuclear physics was atomic physics. At

the beginning of our century, scientists were not yet aware of the existence of the nucleus, and all its manifestations were attributed to the peculiarities and oddities of the mysterious, as it then seemed, atom. The English chemist John Dalton, in the early 19th century, found the first scientific proof of the atomic structure of matter. Yet even a hundred years later, the renowned Austrian scientist Ernst Mach still had some grounds to sarcastically ask those who believed in atoms:

I *"Have you ever seen even one?"*



For a century, the concept of the “atom”, almost devoid of real substance, stirred the imagination and attracted public attention. In the pages of *War and Peace* by L. Tolstoy, *Rudin* by I. Turgenev, *The History of a Town* by M. Saltykov-Shchedrin, and other literary works, the word “atom” likely appeared more often than in the scientific writings of that time. The concept of the “atomic nucleus”, however, had scarcely emerged from scientific circles when it had already gained full definition. Perhaps for that reason, it remained in the shadow cast by the immense popularity of the atom.

The heart of the atom — the nucleus — not only stores and releases all of the atom’s energy, but also determines the atom’s chemical identity; it sets the rhythm of the evolution of giant stars across the vastness of the universe.

Yet what appealed to writers in the idea of the “atom” caused physicists to regard the very notion of the smallest structural unit of matter with scepticism. “Art marvels, science doubts...” wrote M. Prishvin. And science continued to doubt until three great discoveries, made within just a few years at the end of the last century, compelled natural scientists to acknowledge the existence and divisibility of atoms.

The famous English scientist J.J. Thomson discovered electrons — particles that detached from atoms under the influence of electric voltage.

Professor W. Röntgen of the University of Würzburg was the first to observe that under certain conditions, atoms

could emit a powerful electromagnetic signal, which was later called X-rays. And finally, radioactivity was discovered – a phenomenon directly related to the atomic nucleus. Ironically, this strange property of certain substances was initially attributed to atoms. But in the end, the truth prevailed. The study of the invisible, highly penetrating radiation emitted by uranium salt – as established by the French scientist A. Becquerel – eventually led to the discovery of the atomic nucleus.

Discovery is a remarkable event in science. Even more astonishing is the process of choosing that single, always new, always unique path through which a person arrives at it. Indeed, how could invisible rays from a pinch of uranium salt lead A. Becquerel to the idea of a nucleus within the atom? The German poet J.W. Goethe wrote: “... Man must believe that the incomprehensible can be comprehended, otherwise he would not think about it.” A brilliant illustration of science’s central mystery – the transition from total ignorance of something to knowledge – was the brief and turbulent history of the discovery of the atomic nucleus.

One of the natural manifestations of the atomic nucleus’s properties is *radioactive decay*. When a nucleus decays, it emits: heavy, positively charged particles – called *alpha particles*; light, negatively charged particles – *beta particles* (electrons); and *gamma rays*, which carry no charge. This unusual behaviour of nuclei could not fail to attract the attention of scientists. One person asked the direct question: “What happens to the atoms that are the sources

of radioactive radiation?" That person was the future father of nuclear physics, E. Rutherford.

A young scientist, after graduating from the University of New Zealand, came to England for an internship at the Cavendish Laboratory under J.J. Thomson. In the scientific baggage of the future director of one of the world's best laboratories, there was almost nothing except a rather vague idea about the evolution of chemical elements. In fact, it was not even an idea but something like a scientific legend, rooted in the era of alchemy, when it seemed that there were no insurmountable boundaries between different substances.

By that time, chemists had become increasingly convinced that it was impossible to convert one element into another. Based on their observations, they had already established in the eighteenth century the law of the constancy of elements, which stated:

"The quality and quantity of the principles (elements) remain the same; only rearrangements and displacements occur."

This empirical law was reinforced by the periodic table of elements created by D. Mendeleev. The idea of the transmutability of elements appeared to have been expelled from science.

But it was precisely this idea that determined the scientific fate of E. Rutherford. He became extremely interested in radioactivity — this newly discovered property of atoms, as it was then thought. Was it not a hint of the instability

of certain substances?

Ernest Rutherford began his main attack on the problem of radioactivity at McGill University in Montreal, where he had been invited to take up a professorship. At the age of twenty-seven, the young scientist worked with relentless energy. “I’m constantly stuck in the laboratory,” he wrote to his fiancée, “out of seven evenings, I spend five there, and I usually see things through to the end; last Thursday I sent another big article to the journal... it contains a thousand new facts that no one even suspects.” Just as many new ideas were taking shape in his mind.

He enlisted the best researchers at the university to study radioactivity. He began working with electrical engineer R. Owens, who informed Rutherford that, while experimenting with radioactive thorium, he had discovered “something” that was neither thorium nor alpha- nor beta-rays, but which drifted away if blown upon.

Before long, Rutherford proved that the mysterious “something” discovered by Owens was, in fact, a gaseous chemical element – radon – produced during the decay of thorium atoms.

In a sealed vessel containing the radioactive element radon, the scientist eventually discovered another chemical element – the inert gas helium. The conclusion was clear: *a radioactive substance changes as it decays.*

As a result of ten years of persistent and laborious work – which resembled neither purely the work of a physicist

nor solely that of a chemist, and yet was both – Ernest Rutherford found experimental confirmation of the hypothesis regarding the transformability of elements.

Together with the young and talented chemist Frederick Soddy, he discovered three “genealogical trees” of radioactive transformations: those of uranium, thorium, and actinium. The three heaviest elements in the periodic system turned out to be the progenitors of radioactive families, each of which, through a sequence of transformations of its members, ended in the same lighter, stable element – lead.

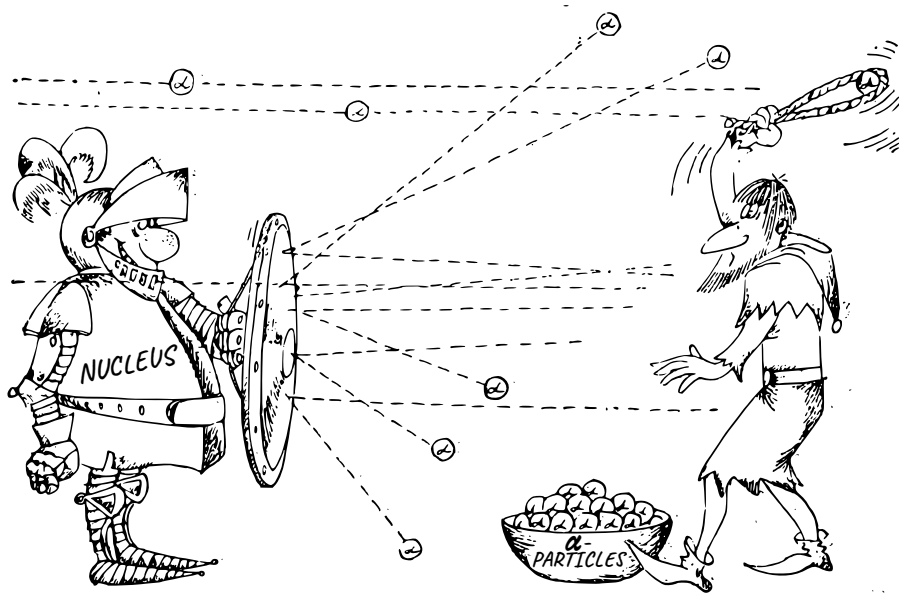
Rutherford and Soddy presented the scientific community with compelling evidence showing that radioactivity was a manifestation of internal changes within atoms.

- “So what? Could the transformation of atoms alone prove they had nuclei?
- “Of course not. Even if Ernest Rutherford had possessed the instincts of a gifted detective, he would still not have guessed that the secret lay in the atomic nucleus.

When faced with the impatient questions of his friend Watson, Sherlock Holmes would sometimes reply that he could make no assumptions yet, as he lacked the necessary facts. Rutherford, too, had no facts that would suggest the existence of a nucleus within the atom. He only knew one thing: *atoms of certain substances could spontaneously*

change. But even this modest conclusion sharply contradicted the prevailing scientific belief in the unchangeability of atoms.

At that time, the periodic system of elements seemed to have eternally fixed each element in its designated place, according to its atomic weight. How then could one question the fundamental tenets of the periodic law — the indivisibility of the atom, the constancy of its mass, and the impossibility of transforming one chemical element into another?



There was practically no theory, nothing to light his path.

The model proposed by J.J. Thomson, in which atoms were imagined as a positively charged sphere filled with electrons, led, as Rutherford felt, into a dead end. His thoughts wandered in a confined space, finding no support.

Yet the experimental results gave him no peace. He must, he was obliged to find out where alpha particles came from at the moment of radioactive decay – particles more than eight thousand times heavier than electrons.

Driven by the need to solve these problems, Rutherford, by then a forty-year-old professor known to the international scientific community, was given full control of a large physics laboratory at the University of Manchester. A spirit of creative energy immediately filled the space.

It seemed as if the very air in the laboratory was charged with the expectation of something extraordinary.

And rightly so. Rutherford's intuition had not failed him. The head of the lab for the first time began conducting experiments not to study radioactive substances themselves, but to observe the interaction of alpha rays with thin films of various materials.

The days of J.J. Thomson's atomic model were numbered.

The unexpected and fascinating turn in the work caught the attention of everyone in the laboratory. "The young men quickly sensed that they were heading into glorious times," recalled one of Rutherford's closest collaborators, Hans Geiger.

And those glorious times did arrive, but only after a heavy price had been paid in hard work. Rutherford's colleagues counted, with their own eyes, more than a million flashes from alpha particles on a phosphorescent screen. And the result more than rewarded all their efforts.

Almost all alpha particles passed through the thin foils without obstruction, deviating only slightly this way or that on the screen. This was to be expected if the atom really consisted only of light electrons. But the behaviour of a small fraction of these micro-projectiles was astonishing. Occasionally, flashes appeared even at the edge of the screen. Only an object with a large charge and mass far greater than that of an electron could cause such strong deflections. What, then, were those rare alpha particles encountering that made them bounce almost straight back?

It became immediately clear that atoms contained something far more substantial than electrons. Rutherford no longer doubted that the positive electric charge and most of the atom's mass were concentrated at its centre – in the nucleus.

The size of the nucleus could also be estimated from the same alpha-particle experiments. Based on the probability of collisions with the heavy atomic cores, physicists calculated the region occupied by the atomic nucleus. Its size turned out to be about 10^{-13} centimetres, while the size of the entire atom was about 10^{-8} centimetres.

A vast university lecture hall and a tiny pinhead at the centre – such was the proportion between the size of an

atom and that of its nucleus.

Thus, nuclear physics was born.

The discovery of the nucleus immediately replaced the old label of atomic radioactivity with a new one – *nuclear*. And now it was nuclear physics that had to answer all questions related to radioactive emissions.

- “But what more was there to answer? It was clear at once: unstable nuclei decay, while stable ones remain unchanged. That’s all.”
- “No, far from it. The discovery of the atomic nucleus did not answer all the questions related to radioactivity.”
- “So what exactly remained unclear?”
- “The nature of the energy source behind the process remained utterly mysterious. What caused alpha and beta particles to be ejected from the nucleus at such tremendous speeds?”

Experiments with X-rays, for example, never caused concern – among either physicists or the general public – about where this radiation drew its energy from.

An electric voltage was applied to an X-ray tube, and electrical energy was converted into electromagnetic radiation. Everything was simple and clear.

But no one connected anything to radioactive uranium, and yet it “worked”. And A. Becquerel, barely recover-

ing from the excitement of discovering radioactivity, was struck a second time when he noticed that the intensity of the uranium salt's radiation did not noticeably change over the course of several days or even months.

The chemical element radium glowed endlessly inside a glass tube, heated its walls, and reliably ionised the air around it day after day, causing the leaves of a nearby electroscope to collapse. Such marvels were often demonstrated during public lectures on radioactivity.



A stunning sight! Energy emerged from a piece of inert matter. The mind refused to grasp what the eyes were witnessing.

It was an unprecedented case. People far removed from science declared this inexplicable energy a mysterious secret of nature. But what did scientists say?

Physicists knew that miracles do not happen, but they could not yet offer anything more definite. In 1903, A. Becquerel wrote in black and white that

| “the source from which (radioactive substances)
draw their emitted energy is unknown to us.”

The source of the energy was unknown – a heavy admission for any physicist.

For centuries, humanity had been convinced that energy never disappears or arises from nothing, but merely changes from one form into another. And now, this hard-won truth, forged over centuries, seemed useless. It threatened to bring down the entire structure of science.

One of the foremost scholars of the time, Henri Poincaré, stated bluntly that “radium undermines the principle of conservation of energy.” It was often repeated like a spell: “If mass is being converted into energy, then mass is not conserved.” And when people recalled that mass had long been equated with matter, since the time of Newton, the thought became truly terrifying. Unable to find the key to the mystery of radioactive energy, some scientists completely lost their bearings. But instead of calling out “Hello?”

like someone lost in the woods, they cried: “Matter has disappeared!”

Other scientists (for instance, the well-known physical chemist Wilhelm Ostwald) used the discovery of radioactivity to justify a long-held philosophical slogan of theirs: that the concept of matter should be abandoned as a “useless mental construct”, and that “the world consists entirely of energetic substance.”

The resolution of specific physical problems touched upon the very foundations of philosophy, and a heated debate broke out among philosophers.

At this moment of unprecedented intellectual confrontation, Vladimir Lenin’s book *Materialism and Empirio-Criticism* appeared. Lenin wrote:

“Matter disappears’ — this means that the boundary to which we have so far known matter disappears, our knowledge goes deeper; those properties of matter which previously seemed absolute, immutable, and fundamental (impenetrability, inertia, mass, etc.) now prove to be relative, inherent only to certain states of matter. For the *only* ‘property’ of matter, the recognition of which is connected to philosophical materialism, is the property of *being an objective reality*, existing outside of our consciousness.”

The further development of physics confirmed the truth of these remarkable words of the great materialist and dialectician.

In radioactive decay, matter did not disappear, the law

of conservation of energy was not violated, and radioactive radiation indeed drew energy that had earlier been stored deep within the atomic nuclei.

Natural scientists had prepared the foundation for this important conclusion. While laypeople stared in bewilderment at the test tube containing radium and scratched their heads, scientists, after a brief moment of confusion, rolled up their sleeves and got to work with vigour.

The renowned French scientist Pierre Curie placed the notorious tube containing radium into a special vessel with water – a calorimeter – to estimate the amount of energy released during the radioactive decay of the substance.

In the water, almost all the alpha particles, electrons, and gamma rays emitted from the sample were absorbed, causing the temperature of the water to rise.

From the degree of heating, Pierre Curie determined that one atom of radium, transforming into radon, released a million times more energy than was produced by the formation of a molecule of water from two hydrogen atoms and one oxygen atom – a chemical reaction well known for its high energy yield.

Radioactive substances came to be seen as something akin to vaults filled with a most precious treasure – energy, which people otherwise extracted laboriously by burning fuel from beneath the earth.

Physicists recognised that there was no fundamental difference between ordinary and radioactive substances.

In their view, atoms of all chemical elements must contain large reserves of energy. But only the radioactive decay of atoms made it possible to detect these reserves, part of which was carried away by alpha particles, electrons, and gamma rays.

The realisation that energy was present all around — close at hand and possibly usable in the future — both delighted and inspired awe.

At the same time, some scientists were already pondering the dangers that this future might hold. Would humanity withstand the trial ahead? Would it use its newfound power for destruction, or would it harness it to accelerate the progress of civilisation?

But few were looking so far ahead. For now, the problem of intra-nuclear energy was of purely fundamental significance, and most scientists were concerned with something else entirely: how to uncover the very essence, to discover the purpose of the energy locked within matter, and to determine when this store came into being.

Still faithful to the law of conservation of energy, they hoped to uncover yet another instance of the familiar energy cycle. All these noble intentions, however, would have remained just that — intentions — were it not for an astonishing development involving atomic weight.

- “Atomic weight? What could be interesting about that? When a nucleus decays, at least something happens – particles are emitted, energy is released. But what could possibly happen to atomic weight?
- “Believe it or not, atomic weight revealed many valuable insights about the micro-world to physicists. Especially when, quite unexpectedly, they found themselves playing the role of auditors.
- “?!”
- “Yes, indeed. The physicist-auditors had an extraordinary stroke of luck. They uncovered a shortfall in atomic weight.

To understand how they managed this, we must turn to... philosophy. Humanity has always longed to know what the world is made of.

More than twenty centuries ago, such questions could only be approached through philosophy – and that is exactly what people did. Democritus, who was evidently more interested in the structure of all things, once declared: “The world consists of atoms.”

His contemporary, Empedocles, approached the problem from a different angle. He sought the elements common to all of nature and concluded that the world was governed by four fundamental forces: earth, fire, water, and air.

Philosophers, of course, were not – and still are not –

required to provide proof. That is why Aristotle, a prominent follower of Empedocles' school, could quite easily assert that matter consisted of a single primary substance, "protyle". No one knew what it was — least of all the philosopher himself.

However, in the early 19th century, the English physician and chemist William Prout seemed to have guessed the nature of this "protyle". The teachings of Democritus and the speculation of Aristotle came together in Prout's hypothesis, forming a harmonious idea of the material unity of the world.

The world, he proposed, was built from atoms, and the atoms of all chemical elements were assembled from the same standard parts — hydrogen atoms. Hydrogen, thought Prout, was the ancient "protyle".

But the 19th century was far more sceptical than the time of the ancient thinkers. A single assertion was no longer enough — proof was required. If Prout's hypothesis were correct, the atomic weights of all elements should be whole-number multiples of hydrogen's atomic weight.

The problem, however, was that no one at the time could actually weigh atoms. Still, the hypothesis was enticing enough to test. The first attempt was made by John Dalton, whom we have already mentioned. Indirectly, by calculating the quantities of substances involved in chemical reactions, he estimated the atomic weights of several elements. And... Prout's hypothesis failed. The atomic weights turned out to have fractional values. Further refinements

did not change this result.

The hypothesis about the typical principle of the universe being built from hydrogen lay forgotten for nearly a hundred years, until physicists took an interest in atomic weight.

At the time, they were casually engaged in the study of radioactivity. They watched with satisfaction as radioactive transformations of atoms of certain elements led to the formation of atoms of new chemical elements, sometimes also radioactive. Struggling to come up with new names, they quickly labelled them with temporary tags like: radium-A or thorium-C. But when the time came to determine the exact position of each of these elements in the periodic table based on their chemical properties, a confusion arose. Some of the substances that physicists easily distinguished by atomic weight and type of radioactive decay were, to the chemists' horror, chemically identical. Where were they to be placed? Suitable empty cells were becoming increasingly scarce.

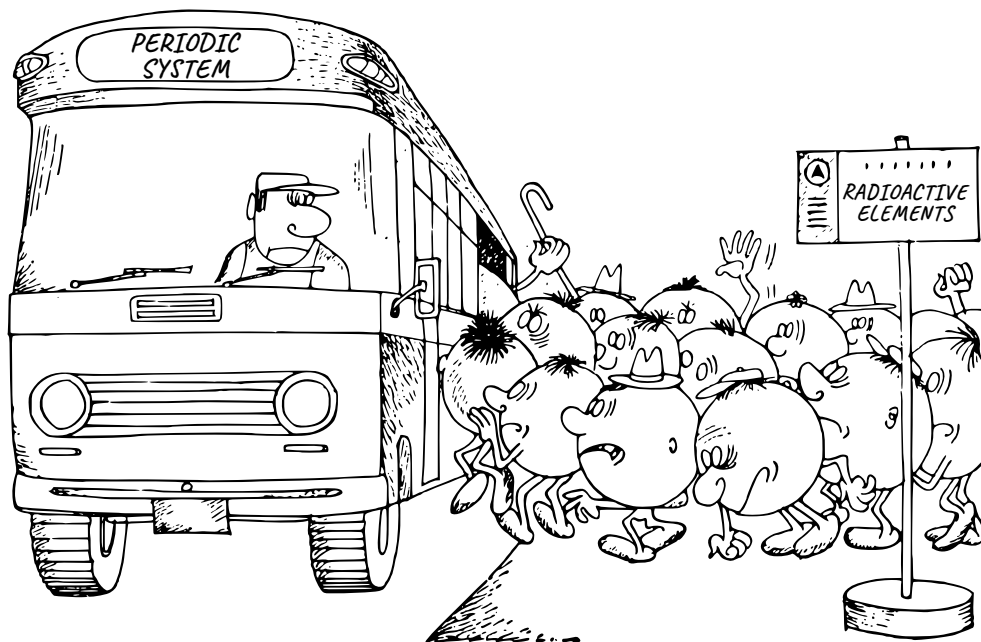
Until then, atomic weight had been the main organising principle in the periodic system of elements. Each element was placed strictly according to its mass: *lighter elements at the beginning, heavier ones at the end.*

But now, several dozen new heavy radioactive elements were vying for just a few available spots.

An unheard-of situation! A competition for places in the periodic table! But elements are not university appli-

CHAPTER 1. FROM ATOM TO NUCLEUS

cants, and the table is not an institution that cannot accept all comers.



Still, if it claimed to be universal, it had to provide room for all elements, however many might suddenly appear.

Eventually, Frederick Soddy, a former colleague of E. Rutherford at a Canadian university, proposed that nature likely contains varieties of chemical elements with different atomic weights and slightly different physical properties, and that these varieties must occupy the same place in the periodic

system.

This last feature was captured in the name they were given: *isotopes* (from the Greek words *isos* – “same” and *topos* – “place”).

The discovery of isotopes among heavy elements, and soon among light ones too, in turn made physicists hold their heads in dismay. Atomic weights had been determined indirectly, using chemical reactions in which isotopes of an element are indistinguishable. There were no illusions left – it was clear that chemical methods would never reveal the weight of each isotope, so physicists decided to take up the precise weighing of atoms themselves using an instrument created specifically for that purpose: *the mass spectrograph*.

The true atomic weight of an isotope could be determined only one way – by weighing each individual atom. The method was as follows: free atoms of a chemical element were first converted into ions. These ions were then accelerated and directed into a vacuum chamber. In the vacuum, under the influence of a magnetic field, the ions travelled along paths whose radius depended on their mass. If the sample consisted of a mixture of isotopes, then a photographic plate placed in the path of the particles would show dark spots in *different locations*, each corresponding to ions of a *different mass*. The number of spots indicated the number of isotopes. The absolute atomic mass of each isotope could be calculated from the position of its spot on the photographic plate.

The very first results completely dispelled a nearly century-old misconception. The fractional atomic weights once assigned to elements were, in fact, arithmetic averages of the atomic weights of all their isotopes.

The weighing of atoms confirmed William Prout's hypothesis: *the atomic weight of each isotope turned out to be a multiple of the atomic weight of hydrogen.*

All seemed to be falling into place: isotopes had been found, atomic weights corrected, and the atomic nucleus discovered.

Like the protagonist of the play *The Bourgeois Gentleman*, who was astonished to learn that he had been speaking prose all his life, physicists too felt a pleasant surprise when they realised that for an entire century they had, in effect, been discussing nuclear mass. After all, the mass of atomic electrons is negligibly small.

Atomic weight, once the supreme authority in the periodic system, completely lost its standing with the arrival of a new idol — the atomic nucleus. The atomic number of elements corresponded exactly to the electric charge of their nuclei and was the same for all isotopes of each element.

Physicists were overjoyed — but not for long. Curiosity is irresistible and recognises no boundaries. They wanted to measure nuclear mass more precisely. And as soon as F. Aston, a close associate of E. Rutherford at Manchester University, completed his improvements to the mass spec-

trograph, a new audit began. That is when the shortage was discovered.

The mass of atomic nuclei fell slightly short – just by a few tenths or even hundredths of a percent of a hydrogen mass – of the nearest whole number.

The experimenters could only throw up their hands. To them, atomic nuclei now appeared not only as keepers of vast energy reserves, but also as squanderers of their own mass.

- “Theft in the microworld? Phenomenal! So what did the investigation reveal?
- “Explaining the tiny loss in atomic weight turned out to be far more difficult for physicists than it would be for a detective to catch the craftiest thief.
- “In the world of atoms and nuclei, nothing is simple. I suspect that two plus two is not exactly four there, and ordinary mathematics does not apply.
- “The culprit was not arithmetic, but the very foundations of the universe. The minuscule missing fractions of a gram, the so-called “mass defect,” were found – with the help of the special theory of relativity – to be a mathematically exact measure of the energy of radioactive radiation.

Scientists, absorbed in the study of atomic nuclei, did not at first realise that the evidence they needed had already been uncovered several years earlier by the special

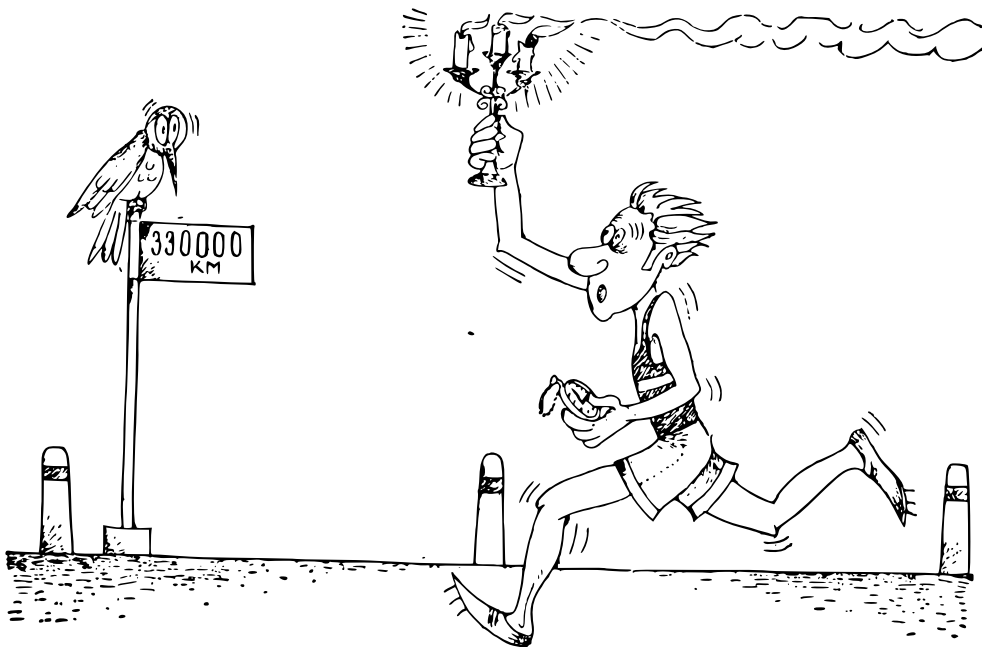
theory of relativity – the very theory that had upended all previous notions of space, time, matter, and motion. However, it would be wrong to think that the leading theorists of the early twentieth century had set out with the explicit aim of clearing a path toward an understanding of the microworld.

At that time, neither the path itself nor the obstacles that needed to be overcome were yet visible. Nothing was known about the atomic nucleus. Only one thing was clear: *atoms had a complex structure*. After all, they contained electrons, and during radioactive decay they emitted alpha, beta, and gamma rays.

Experimentalists were primarily engaged in studying the properties of radioactive substances and had only just begun to provide material for theorists to ponder. The window into the microworld had barely been opened.

Nevertheless, in the early years of the twentieth century, the superficial approach to the fundamental interconnections in nature – which had dominated physics for several centuries – was exposed and decisively rejected. Science formulated new, deeper foundations on which the physics of the atomic nucleus and elementary particles was later built. How could this have happened?

Typically, the revision of old concepts occurs when they come into conflict with new experimental facts.



At that time, physicists trying to understand the structure of matter had one unusual discovery at their disposal – the radioactive decay of atoms. However, the phenomenon of radioactivity was so incomprehensible that it was impossible to determine precisely how it contradicted the existing worldview.

“There was no good fortune, but misfortune helped,” says the proverb. There was another fact that clearly contradicted Newtonian mechanics. Renowned scientists such

as H. Lorentz, A. Poincaré, P. Langevin, and others were attempting at the time to reconcile classical physics with a strange property of light discovered by experimentalists: its speed was entirely *independent* of the motion of the source emitting the light. Whether the source was approaching or receding from the receiver, the light always reached it at the *same speed*. The rule of addition of velocities simply did not apply to light!

The scientist who obtained the results without which it would be impossible to construct a single particle accelerator, to assess atomic energy reserves, or to calculate the energy balance of nuclear reactions, did not, like E. Rutherford, study radioactivity or search for the atomic nucleus, nor did he discover any elementary particle. His entire laboratory, all his tools of work, could easily fit into a pocket. It was a pencil, which he used to carry out the necessary calculations.

A. Einstein was the first to understand what lay behind the “disobedience” of the speed of light to the usual laws of classical physics. He showed that this fact, along with the mathematical formulas that had been devised to eliminate the contradiction between it and Newtonian mechanics, must serve as the foundation of a new theory – the *Special Theory of Relativity*. The old rules, he said, should be regarded as approximations, valid only for objects moving at speeds much lower than the speed of light.

The Special Theory of Relativity stated that the *faster* a body moves, the more it resists motion by *increasing*

its mass. This unusual metamorphosis could be observed only under one extremely strict and, at the time, seemingly unachievable condition: the body had to move at a speed close to that of light.

The new theory was created as if “to order” for the microworld, although slightly earlier than it became relevant. On Earth, there simply were no known objects moving at such high speeds. This prompted E. Rutherford to remark at one point that, in his view, the drawback of the Theory of Relativity lay in its excessive abstraction and its detachment from reality.

In fact, the change in mass of a body moving at nearly the speed of light, as predicted by the theory, had already been observed by the famous J.J. Thomson. Having discovered the electron in a discharge tube, he measured its mass and realised that *a fast-moving electron was heavier than one at rest.*

Finally, six years later, E. Rutherford discovered the atomic nucleus and opened a window into the microcosm – a realm populated by reckless particles with immense energies, a world entirely beyond the reach of classical physics.

The microworld became a magnificent arena in which the theory of relativity could display its full depth and comprehensiveness.

In neither the macroworld nor the world of atomic nuclei and elementary particles is there anything that lies

outside the four fundamental concepts: *space*, *time*, *matter*, and *motion*.

The founders of dialectical materialism, K. Marx and F. Engels, long before the development of the theory of relativity, asserted that if time and space are forms of the existence of matter, then they must be most intimately connected with matter and with each other, and that a relationship between matter and motion must necessarily be revealed.

However, at that time, natural science offered no concrete confirmation of these philosophical principles. No experiment contradicted the naïve belief that space was a “void container filled with material bodies.” Nor was anything seen to challenge the belief in some absolute time, independent of the properties of matter.

The theory of relativity, for the first time in the history of science, demonstrated how closely the properties of space and time are truly intertwined.

Shortly after Albert Einstein’s article on the special theory of relativity was published in the journal *Annalen der Physik*, he wrote an important reflection in a letter to a friend: *that the mass of a body must be a direct measure of the energy it contains*.

At the time, the results of delicate experiments were already known, masterfully conducted by the eminent Russian physicist P. Lebedev, who had shown that light exerts pressure on the surface of objects.

“Light carries mass,” wrote Einstein. “Noticeable loss of mass ought to be observable in radium. Such thoughts are amusing and appealing; but whether the Lord is laughing and leading me by the nose — I cannot know.” Einstein’s humorous doubt proved unfounded. He would later formulate his thoughts on the relationship between mass and energy in a concise three-page article, which he published a few months later in the same journal.

“Does the Inertia of a Body Depend on Its Energy Content?” — the title posed the question. The article answered it in the affirmative.

New conceptions of space and time enabled Albert Einstein to prove a general principle: the close interconnection between mass — the measure of a body’s inertia — and energy — the measure of its motion. Investigations of the microworld confirmed the conclusions of his theory.

The seemingly impassable gulf between matter and motion, which had previously appeared insurmountable to scientists, was now permanently closed — a gulf whose existence had never been acknowledged by the founders of dialectical materialism.

Einstein demonstrated that the increase in the mass of a moving body is linked to the increase in its kinetic energy. The mass of a body at rest — its so-called *rest mass* — is associated with its full reserve of internal energy. This reserve consists of the energy of molecules, atoms, atomic nuclei, and elementary particles.

Einstein's formula $E = mc^2$, indicated that with any change in mass, energy changes proportionally, but with a huge proportionality constant, c , the speed of light (3×10^{10} centimetres per second), squared. Here, energy E is measured in joules, and mass m in grams.

It is practically impossible to detect a change in rest mass, for example, in substances involved in chemical reactions, since the portion of released energy is too small. "It is not excluded," Einstein wrote, "that the theory might be verifiable for bodies whose energy content is extremely variable... for instance, for salts of radium."

The brilliant scientist had hit the mark! In doing so, he had pre-emptively prepared the crucial material without which the case of the mass defect – and with it the problem of intra-nuclear energy – could not be solved.

Here, two seemingly separate lines of scientific development met: the direct experimental investigation of radioactivity and the theoretical exploration of the deepest properties of space and time.

This convergence allowed for the door to the atomic nucleus to be thrown open even wider in the future. Einstein later said:

"I focused my efforts on abstract theory, whereas Rutherford achieved deep understanding through relatively simple reasoning and the use of comparatively simple experimental means."

Together, Ernest Rutherford and Albert Einstein carried out the very first essential work required to enter the mi-

croworld.

Such giants as Newtonian concepts of space and time and the law of the constancy of mass were swept aside.

Einstein's famous formula compelled everyone to look at radioactive decay in a new light. There was no longer any need to approach it from two separate summits – the law of conservation of energy and the law of conservation of mass. It was now enough to ascend a single, higher and more comprehensive peak – the so-called *unified or generalised law of conservation of mass and energy*.

From this vantage point, it became clear that any loss of nuclear energy during radioactive decay must necessarily be accompanied by a loss of mass.

At the very first Solvay International Conference on the structure of matter in 1913, shortly after the discovery of the atomic nucleus, French physicist Paul Langevin was the first to express the idea that the mass defect in isotopes, according to the formula $E = mc^2$, was directly linked to changes in the energy of atomic nuclei.

- “So, according to Einstein’s formula, can one determine the nuclear energy reserve corresponding to the size of the mass defect?
- “A deficiency in mass indicates a loss of energy, not a reserve. The very existence of any system composed of smaller parts – including the atomic nucleus – is secured by the energy released during its formation.

- “Then from what reserves does radioactive radiation draw its energy?
- “Heavy, unstable nuclei have a smaller mass defect than more tightly bound medium-weight nuclei. The energy corresponding to the difference between these deficits is what fuels the instability of heavy nuclei. It is this excess that, when released, may cause the nuclei to disintegrate violently, imparting tremendous speed to the emitted radioactive particles.

Understanding why atomic nuclei are taxed for the right to exist only became possible once physicists investigated the internal structure of the nucleus.

The earliest data on the charges and masses of atomic nuclei – regarded as point-like – already suggested that these points themselves were *composed of other particles*.

But what exactly could a nucleus be made of?

The idea of W. Prout – that the atoms of all elements are built from atoms of the lightest element, hydrogen – when translated into the language of nuclear physics, took the following form: *all nuclei consist of hydrogen nuclei*.

Indeed, from hydrogen nuclei (now called *protons*), one could easily construct the mass of any isotope, and their individual positive electric charges accounted for the total charge of the nucleus.

Only one issue caused concern – and it could not be ignored. If one simply added up the positive charges of all

the protons needed to build a nucleus of a given mass, the result exceeded the actual charge of that nucleus.

There was no escape. Physicists had to compromise and accept that nuclei could *not* consist of protons alone. *Something* had to neutralise *some* of the protons' positive charges.

This might have been the time for imagination to soar... but harsh reality clipped its wings. The choice of suitable building materials for nuclei was extremely limited. Physicists had to make do with what was available – and besides the proton, science recognised only one other particle: the electron, carrying a single negative electric charge. Its mass was small, so electrons could, in principle, neutralise a number of proton charges *without* significantly affecting the total mass of the nucleus.

However, it soon became clear that protons and electrons were incompatible as cohabitants of the nucleus – a realisation that caused physicists considerable trouble in explaining many nuclear properties.

Only twenty years later did E. Rutherford's student, James Chadwick, discover the proton's true nuclear companion – the *neutron*. This new elementary particle had nearly the same mass as the proton, but crucially, it carried *no electric charge*. It was exactly what was needed.

With this, the old motif of the unity of matter's structure sounded again – now arranged in a new harmony of neutron-proton composition.

And it was in this harmony that the long-awaited clarity emerged: *a full explanation of the phenomenon of radioactivity as transformations involving nuclear protons or neutrons.*

For example, beta decay is nothing more than the transformation of one of a nucleus's neutrons into a proton and an electron. The proton remains in the nucleus, while the electron is ejected. As a result, the original nuclear community of nucleons (the collective term for protons and neutrons) gains an extra proton. The nuclear charge increases by one, and the atom becomes an atom of an element whose atomic number is one unit higher.

There remains just one final point to understand: Why is the total mass of protons and neutrons within a nucleus always *less* than the sum of the masses of the same number of free nucleons?

One could give a short answer: because the neutrons and protons in the nucleus are *bound* together. But that immediately invites the follow-up question: "What does it mean to be bound?"

Unfortunately, there is no exact analogy in the macroscopic world for what happens to nucleons within a nucleus. Superficial comparisons with glue or cement are also inadequate.

Perhaps this image may help:

Nucleons are bound together by a sort of tax, which nature — the strictest of auditors — collects at the moment the nucleus is formed.

By surrendering a portion of their energy, free protons and neutrons come under the influence of powerful nuclear attraction forces, which operate over distances comparable to the size of the nucleus.

And according to Einstein's formula, $E = mc^2$, to lose energy is to lose mass. Thus arises the *mass defect* – the shortfall in the total mass of the atomic nucleus.

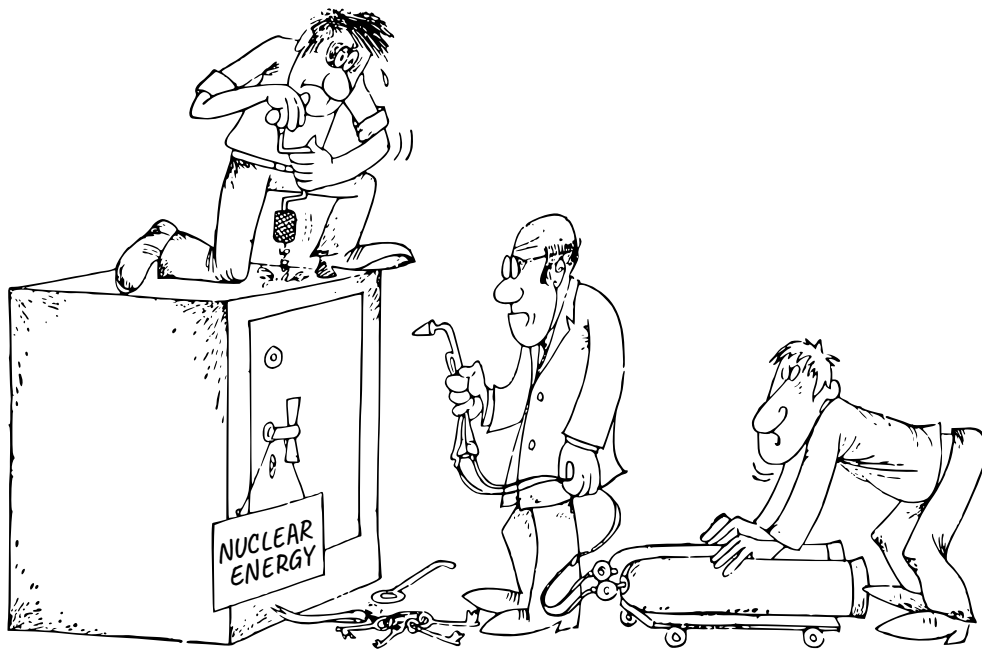
The energy paid by a nucleus for the right to exist – and equal to the energy that would be needed to separate it into individual nucleons – is called *binding energy*. The greater this energy, the harder it is to break apart the nuclear system of nucleons.

As it turns out, nature collects less “tax” per nucleon from the lightest and heaviest nuclei than it does from nucleons in medium-weight nuclei.

The excess energy that light and heavy nuclei have possessed since their formation – somewhere in the depths of giant stars – became a precious gift from nature to humankind.

In stable nuclei, this gift is stored as securely as money in the fireproof vaults of a bank.

The tempting surplus of energy was contained both in a lump of uranium and in a flask of heavy water, whose molecules include the heavy isotope of hydrogen – *deuterium*.



But it was impossible to make use of this energy: like a real-life magic coin that could not be spent, straight out of a fairy tale.

Only the spontaneous radioactive transformation of heavy nuclei could open the door to this vault. And right under the physicists' noses, alpha particles, electrons, and gamma quanta would scatter part of the stored energy in all directions.

Humanity was faced with a task of immense importance

– to learn how to unlock the stores of nuclear energy. For a long time, scientists did not know how to achieve this, as they lacked the necessary tools.

In chemical reactions, substances release energy only during the rearrangement of the electron shells of atoms and molecules. The discovery of radioactivity further confirmed that atoms of heavy, unstable elements emit part of their internal energy only when their nuclei undergo transformation. But how could one induce a nuclear reaction?

Chemists had never faced such difficulties. With the help of an ordinary spirit lamp, they could easily supply reacting molecules with the few electron volts needed to start a chemical reaction. But to reorganise the tightly bound collective of nucleons demanded much greater effort, for the binding energy of nuclei reached tens and even hundreds of millions of electron volts.

Once it became clear that with less than a million electron volts no nucleus could be altered, physicists tried bombarding light atomic nuclei with projectiles such as alpha particles from radioactive radiation. And suddenly there was success. Alpha particles with energies of several million electron volts so disturbed nitrogen nuclei that they broke apart into oxygen nuclei and protons. This was a nuclear reaction, carried out at human will.

“Rutherford was the first human being,” wrote Louis de Broglie, one of the founders of quantum mechanics, “who was fortunate enough to realise the age-old dream of the

alchemists – to artificially transform one chemical element into another.” But whereas the alchemists sought only to obtain gold from base materials, the success of “nuclear alchemy” gave humanity a far more valuable treasure – a new source of energy.

Observing the first nuclear reaction – the splitting of nitrogen nuclei – E. Rutherford noticed that the protons he recorded carried away from the decaying nucleus more energy than the alpha particles had brought into it. Thus, for the first time, a researcher managed to slightly open the nuclear safe containing stores of energy.

Later it was discovered that some other nuclei also split with the release of energy. Chemical reactions in which energy is released are called exothermic. Nuclear reactions received the same name. But what a difference in the amount of energy released! The rearrangement of a single molecule in a chemical reaction yielded, at most, only a few electron volts. The generosity of a nuclear reaction astonished contemporaries. The very first split nucleus (a nitrogen nucleus) endowed the emitted proton with energy a million times greater.

Hearing of the experiments on splitting nuclei, F. Soddy wrote in 1919:

These discoveries have shown that the grim struggle for existence, for the exhausted sources of natural energy which humanity has carried on until now, is not at all the sole and inevitable fate of man. Nothing prevents us from believing that the day will come when we shall be able to use for our needs the pri-

| mary sources of energy which nature jealously keeps
for the future.

Amid the chorus of admiring voices, stirred by new scientific achievements and filled with hope for solving the age-old problem of fuel, one lonely voice of a poet went unheard:

| The world burst in Curie's experiments
As with an atomic – exploding bomb...

wrote A. Bely in 1921 in his poem *The First Meeting*.

But people were not yet inclined to listen to the fore-sight of feelings; they did not trust what was not based on calculations and formulas. Yet the coming danger lay precisely in the realm of emotions and moral foundations. Already during the First World War there arose an interest in the question of using radioactive radiation for military purposes.

E. Rutherford was compelled to declare that scientists sought to use the internal energy of radium for the purposes of knowledge. "Fortunately," added the father of nuclear physics, "at present we have not found a method for applying the energy of radium," and he expressed the hope that it would not be found until "man lives peacefully with his neighbours."

At that time, however, there were no special grounds either for alarm or for enthusiasm.

Chemical reactions still had a very important advantage over nuclear ones. For example, combustion reactions

were self-sustaining; they involved at once a large mass of matter, whereas nuclear fission reactions remained only occasional flashes of sparks.

Nuclei, compared with molecules, possessed immense energy, but released it only when struck by an alpha particle. The likelihood of such an event was no greater than the chance of hitting a fly's eye with a shotgun while it sat on the top of a tree. In experiments, only one in 100,000 alpha particles struck the nucleus of a light atom. In the case of a heavy nucleus, even fewer succeeded – only one particle in a million.

The situation did not change even after the launch of the first proton accelerator in E. Rutherford's laboratory. New exothermic nuclear reactions were discovered – and nothing more.

The treasure – nuclear energy – lay close at hand. Man had learnt, "with his own hands," to obtain a small portion of nuclear "fire," but there could as yet be no question of its practical use.

The discovery of natural radioactive substances, which emit small portions of intranuclear energy over many years, somewhat resembled the acquisition of an "eternal candle". But the gain in energy from nuclear reactions caused by accelerated protons was no greater than a penny prize received at a shooting gallery by an unlucky fellow who had squandered his entire salary on shots. Much more energy was spent on accelerating the particles than was released as a result of the reaction.

What optimism could there be! Even in 1937, E. Rutherford said: “The prospect of obtaining energy from artificial processes of transformation does not look promising.”

He turned out to be right. It was impossible to obtain energy in the quantities humanity needed from individual exothermic nuclear reactions.

– “But does there exist at all such a reaction in which a nucleus would immediately give up its entire energy reserve?”

– “In principle, physicists knew how to obtain this reserve in full. Their confidence was bolstered by the ‘mass defect’. Maximum energy could be released by transforming the nucleus of the heaviest element into the nucleus of an element from the middle of the table. The difficulty lay only in how to break the heavy nucleus into smaller ones.”

– “And would it not be simpler to combine the lightest nuclei, which also seemed to have a small ‘mass defect’ and an excess of energy?”

– “Such reactions take place in blazing stars. But in the laboratory the accelerator consumed so much energy to bring together two nuclei, for example, of the hydrogen isotope — deuterium — that talk of a possible gain sounded like a mockery. And yet, scientists soon managed to find a way to master nuclear energy.”

In 1934, the French scientists F. Joliot-Curie and his wife I. Curie, the daughter of the famous M. Skłodowska-Curie,

discovered a new phenomenon — the artificial radioactivity of atomic nuclei. The Joliot-Curies irradiated aluminium nuclei with alpha particles. As a result of the nuclear reaction, a radioactive isotope of phosphorus that does not exist in nature was obtained for the first time.

Thus, forty years later, the unique character of the natural radioactivity of atomic nuclei was lost. Humanity had learned to transform any stable substances into radioactive ones by bombarding the nuclei of various chemical elements with protons, neutrons, and alpha particles.

Neutrons played a special role in the creation of artificial radioactive isotopes. These particles have no electric charge, and therefore they easily overcame the electrostatic barrier (like charges repel) that surrounds heavy charged nuclei.

A young but already well-known Italian scientist, E. Fermi, preferred to work with neutrons. The discovery of the French scientists interested him greatly. A theoretical physicist at the University of Rome and the creator of the theory of radioactive beta decay, he decided, together with his colleagues, to begin experiments on irradiating heavy nuclei with neutrons.

Why heavy ones in particular?

E. Fermi conceived of stepping beyond the boundary of the periodic table and creating an element whose nuclei would contain more protons than those of the heaviest known element. The scientist was convinced that neu-

trons, entering uranium nuclei already overcrowded with nucleons, would force them into radioactive beta decay. And if so, the uranium nucleus would acquire the much-desired additional proton.

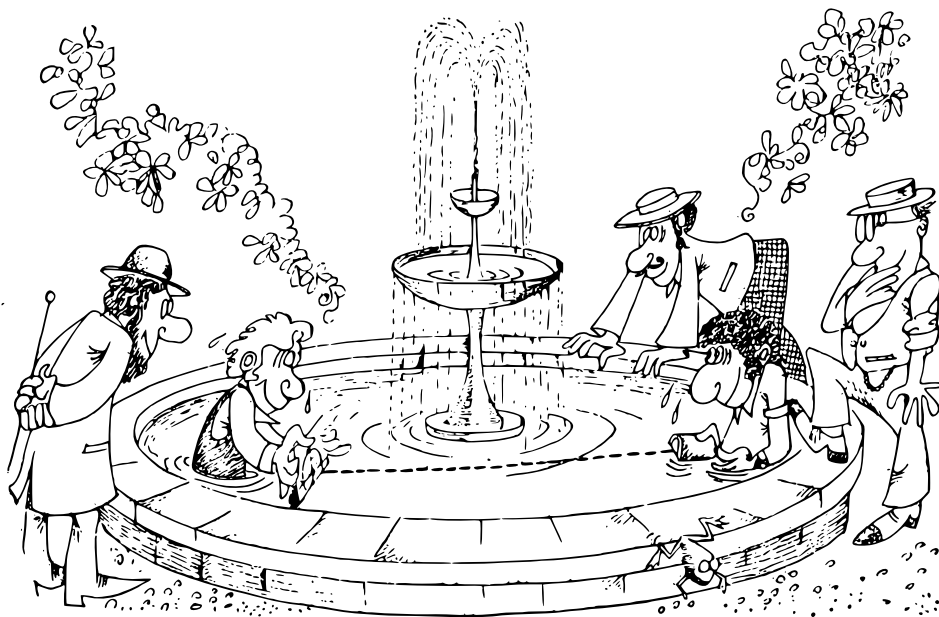
The equipment required for the neutron attack on uranium consisted of a neutron source, a uranium target, and a box with lead walls lined inside with paraffin, intended to protect the experimenters from radioactive radiation.

The box might not even have been worth mentioning, but its completely unexpected effect on the measurements led Fermi to a discovery that significantly accelerated the path to mastering nuclear energy.

After several experiments, the scientists were astonished to find that in different parts of the box, uranium would “swallow” neutrons with varying appetite, so to speak. Mysticism? An annoying interference?

Fermi saw something more in this. The next morning he came to the university with a ready explanation. And shortly afterwards, on one of the streets of the Eternal City, a strange scene unfolded. A group of young men burst out of the university gates and ran straight to the nearest fountain. They lowered into the water the neutron source, the target, and... Fermi’s idea was brilliantly confirmed.

Having reflected on the results of the previous day, E. Fermi proposed the following. The matter probably lay in the fact that the absorption of neutrons by heavy nuclei depends on the energy of the neutrons themselves.



Water is an excellent moderator for neutrons. Colliding with the nuclei of hydrogen – protons – the neutral particles are quickly slowed to the speed of the thermal motion of water molecules (such neutrons are called thermal). Once slowed in the depth of water, thermal neutrons were far more likely to be captured by uranium nuclei. On that memorable day the fountain became a crucial part of the experimental apparatus.

The discovered phenomenon fully explained the earlier

puzzle with the box. Reflecting from the paraffin blocks, the neutrons lost energy, slowed down, and entered reactions with target nuclei far more readily. Only in different parts of the box, because of its shape, was the number of such slowed neutrons uneven. That was all the mystery.

At last the day arrived when it was possible to begin the analysis of the newly obtained radioactive nuclei. The silence of the university corridors was time and again broken by the sound of hurried footsteps — another member of E. Fermi's group, or Fermi himself, rushing to the chemistry laboratory with an irradiated target in hand.

And then the results: a new radioactive element was detected!

E. Fermi called it "transuranic", that is, positioned in the periodic table beyond uranium.

But this was not the final act, only the prologue to a story rich in consequences for uranium. Other scientists, too, were carrying out experiments with uranium bombarded by thermal neutrons. A "nuclear fever" swept through many laboratories of the world. In 1938, I. Joliot-Curie and the Yugoslav physicist P. Savić repeated Fermi's experiment, but obtained a completely opposite result.

In the irradiated target they discovered isotopes of elements no heavier than uranium, but resembling in their chemical properties those from the middle of the periodic table.

So what kind of nuclei were actually being produced?

Superheavy, or on the contrary, lighter ones? Who was right — E. Fermi, or I. Joliot-Curie and P. Savi-?

Both experimentalists and theoreticians were intrigued. The problem was studied intensively not only in Paris, but also in Germany and Sweden.

In fact, there was no contradiction at all. When a uranium target was irradiated, not only was a new transuranic element formed, but also about twenty lighter chemical elements. To each of them one might well have asked: "Mask, who are you?" No one suspected that beneath two of the simplest — barium and lanthanum — were hidden the witnesses and participants of an entirely unusual reaction: the fission of uranium nuclei. It was this reaction that revealed to humanity the energy locked within nuclei since the time of their formation.

The task of identifying all the components of the isotopic mixture obtained by Fermi was completed only in 1939, thanks to the efforts of such scientists as I. Joliot-Curie and P. Savi-, L. Meitner and O. Frisch, O. Hahn and F. Strassmann.

When the fog of assumptions, errors, hypotheses, and old ideas had finally cleared, all the isotopes obtained by irradiating uranium with neutrons were placed into their proper cells of the periodic table.

First of all, it was established precisely that the uranium target consisted of two isotopes of uranium with atomic number 92 and nucleon numbers 235 and 238.

Uranium-238, as Fermi had supposed, captured a neutron and was transformed into radioactive uranium-239. One of the neutrons in this nucleus then changed into a proton and an electron. This additional proton raised by one the atomic number of the element.

Fermi had indeed produced the nucleus of the first transuranic element – the ninety-third – which was named neptunium.

Neptunium, in its turn, underwent beta-radioactive decay and was transformed into the nucleus of the next transuranic element, which received the name plutonium.

But the report from Paris was equally correct.

The nuclei of the lighter isotope of uranium, on absorbing thermal neutrons, performed a breathtaking “trick” – a leap across several tens of cells in Mendeleev’s table. They split into two almost equal parts; from a single heavy uranium nucleus arose two nuclei – one of the element lanthanum and one of the element barium, both belonging to the lighter category.

The radical restructuring of this vast, loosely bound system, made up of several hundred nucleons, into tightly bound small groups of nucleons in medium-weight nuclei, of course, did not occur without some “shrinkage” and “settling.”

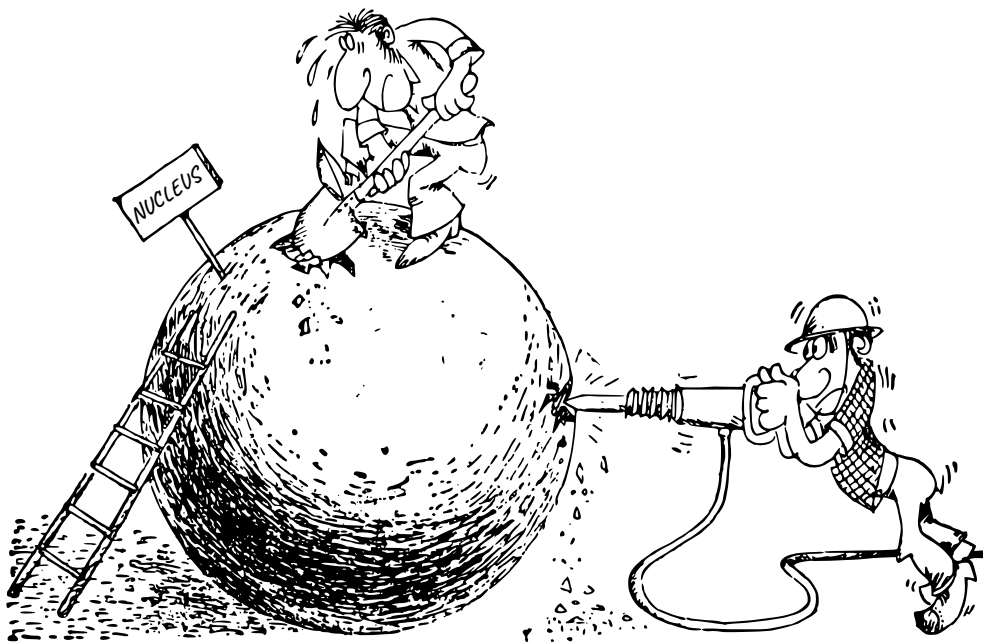
The “mass defect” of the new isotopes was greater, and according to the formula $E = mc^2$, it could be calculated that the fission of each uranium nucleus must release

about 200 million electron-volts of energy. Experiment confirmed the reality of this figure.

- “Yes, this number is astonishing. Has the dream of mankind at last been realised, and have they obtained a new source of energy?”
- “No. The fission of individual nuclei still does not provide a practically usable output of energy.”
- “Why not?”
- “Because it cannot compete with the chemical reaction of combustion, in which an enormous number of molecules participate at once. If only the fission reaction possessed such a property!”
- “So, mastery of nuclear energy depended entirely on how the fission reaction proceeds?”
- “In essence, yes.”

As early as 1935, F. Joliot-Curie, in his Nobel lecture, said:

“If we look back and embrace with our vision the progress of science, which is advancing at an ever-accelerating pace, we have the right to believe that researchers, who create or destroy elements at will, will be able to achieve transformations of an explosive character, to achieve genuine chain reactions. If we can carry out such transformations, then it will be possible to release an immense amount of energy that can be put to use.”



Not single fission reactions of the uranium nucleus, but chain reactions, in which atomic nuclei of large mass take part – this was the only path that could lead to the practical use of nuclear energy. Before the discovery of fission, nothing was known of this path. But in 1939, F. Joliot-Curie already knew where to look for it.

The fission of each uranium nucleus is accompanied by the birth of several neutrons. It would seem that these neutrons could, in turn, cause the fission of new nuclei, and a large mass of matter would be drawn into the reaction.

Yet the final conclusion about whether chain reactions in uranium could develop depended on the number of neutrons released during fission.

Thus the question, “Will humanity gain a new source of energy or not?” could be posed more concretely: “How many neutrons are emitted during the fission of a single uranium nucleus?” If, on average, they turned out to be fewer than two and a half, the fission reaction would have remained of purely scientific interest.

F. Joliot-Curie, working with G. Alban, established that on average about three secondary neutrons are emitted in uranium fission. This fact immediately showed that chain nuclear reactions were indeed a real means of obtaining nuclear energy.

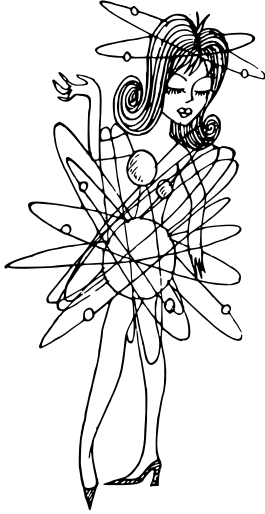
In the world's largest laboratories, proton accelerators were created. In vast installations resembling factories, scientists, using the most intricate instruments, followed the instant of encounter between two free nucleons. The particles collided, scattered, new particles appeared – yet the mystery of the structure of the nucleus remained unsolved. It was thought that just a little more patience, another series of experiments, a further increase in proton speed, and the fundamental principles of nucleon behaviour in nuclei would be revealed. But... as accelerators grew in size and power, as the protons they propelled became ever faster, and as observations multiplied, the nucleus remained as enigmatic and full of secrets as the smile of Leonardo's Mona Lisa.

The expectations of nuclear physicists were not fulfilled. Brief encounters of high-energy nucleons bore little resemblance to the relationships within a long-lived cluster of nuclear nucleons, saturated with powerful nuclear forces. The higher the energy of the collisions, the more likely it became that entirely new particles would be born — particles with no direct connection to the nucleus.

Quite unexpectedly, before physicists opened a densely populated world of elementary particles, and hundreds of new, immensely difficult questions arose. These became the domain of a field that had grown from the depths of “Nuclear Physics” — the “Physics of Elementary Particles”. Meanwhile, researchers of atomic nuclei undertook the arduous task of uncovering the deeper layers of the hidden properties of nuclei.

Everything known about the heart of the atom pointed to one conclusion: the nucleus could not be regarded as a community of isolated nucleons, any more than an organism can be considered a mere sum of its many cells.

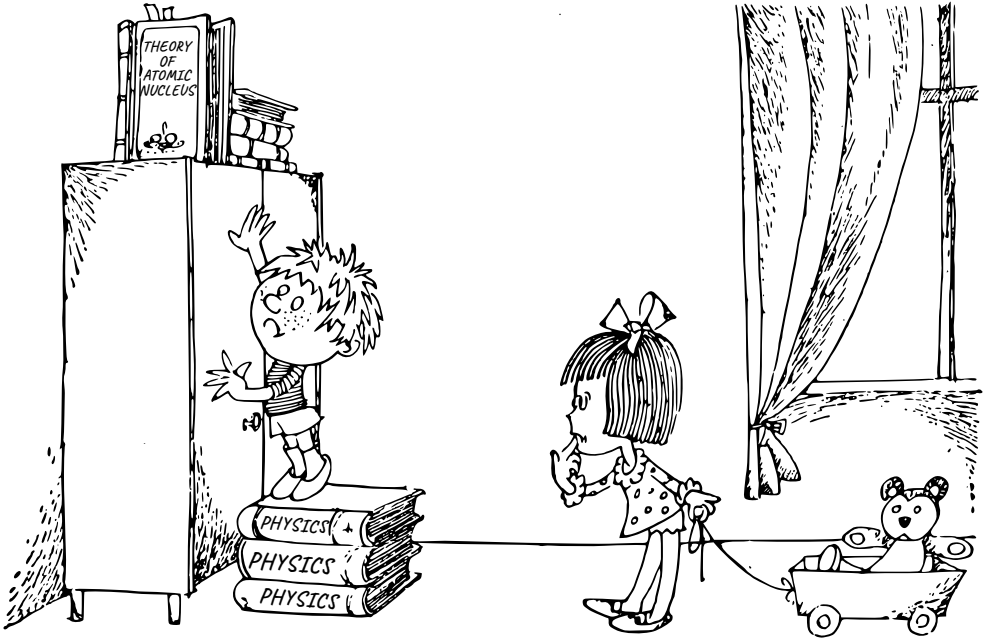
HOUSE OF MODELS



2 House of Models

- “So it turns out the first assault on the nucleus did not quite succeed? Physicists rather easily seized some of the bastions and carried off a rich trophy – nuclear energy – but the fortress itself has not fallen?! What will the next assault look like, and is there an overall strategic plan for the whole operation?”
- “Battles are being fought continuously in every direction, yet no general plan exists as of now. To draw up a unified plan for conquering the secrets of the nucleus is no easy matter, given the strangeness and inaccessibility of the forces that guard the atomic stronghold.”
- “Since the discovery of the tiny fortress at the centre of the atom, a third generation has already appeared on Earth, and none of them has ever had cause to complain of any discomfort brought about by ignorance of nuclear forces. The reason is that these forces do not reveal themselves in our everyday lives – not like

gravity or electricity! And yet, these forces, inaccessible to direct human experience, form the foundation of far more powerful and all-embracing processes in nature."



Gravitational fields, permeating the vast expanses of the cosmos, shape galaxies and stellar clusters — yet it is nuclear reactions that ignite these stars. It is beyond doubt that the world around us is densely saturated with the most diverse electromagnetic phenomena. Biological, chemical,

and many other processes are regulated by these interactions. Yet the entire variety of stable substances is once again ensured by the nuclear forces that bind protons and neutrons within the atomic nuclei of chemical elements.

For the first time, these mighty forces made themselves loudly known when E. Rutherford, with the aid of alpha particles, gave the atomic nucleus a “flick on the forehead.” At first, physicists could not determine precisely who had struck back. The first suspicions fell upon familiar forces – gravity and electromagnetism. But the former candidate was quickly dismissed: elementary particles are so light that even at the minuscule distances within the atomic nucleus they barely feel one another’s gravitational pull. Matters were somewhat more complicated with the second candidate.

Extremely sensitive to changes in distance between charges, electromagnetic interaction multiplies its strength manifold in the microworld. Ordinary electrostatic attraction holds all the atomic electrons around a positively charged nucleus, and in some heavy elements their number reaches a hundred. Electrostatic forces also act within the nucleus. But they cannot serve as its cementing bond: all protons, having the same positive electric charge, repel each other and strive to tear the nucleus apart. Sooner or later, this disintegration is bound to occur.

At last, another mystery remained: what keeps the neutral particles – neutrons – imprisoned within the nucleus? At first, scientists assumed that magnetic attraction might

play a role, but these forces were far too weak to bind neutrons to protons.

The arguments against quickly outweighed the case, and this second hypothesis had to be abandoned.

Nothing remained but to assume that inside atomic nuclei there must be new, previously unknown forces – forces so powerful that even electromagnetism was weaker by a factor of $1 : 10^4$. Theorists now faced the task of creating a theory of the atomic nucleus, and this new circumstance hardly made their work easier; it only made it more demanding.

Quantum mechanics seemed, at first glance, a promising foundation for such a theory of nuclear interactions, by analogy with electromagnetic forces, which were already understood as arising from the exchange of photons.

By following this analogy, and the conventions of rigorous theory, one had to accept that there exists a special field of nuclear forces, along with particles – quanta of this field. Protons and neutrons, by exchanging these quanta, could thus be held together inside the nucleus.

Unfortunately, no one could immediately point to a suitable particle that might serve as the carrier of nuclear forces. Only fifteen years after the discovery of the neutron did experimenters detect, in cosmic rays, the pi-meson – a particle that could indeed act as the messenger of nuclear interaction.

Theorists were encouraged. Now it seemed possible,

at least in principle, to isolate a pair of nucleons from the nucleus and, as if on a strip of film, record their exchanges of pi-mesons in the language of equations. From there, it seemed, one might eventually reach a general plan.

This approach was hardly new. Pushkin's Salieri had once remarked:

*Silencing the sounds,
I dissected music like a corpse.
I trusted algebra to reveal harmony ...*

But when applied to the nucleus, the task proved so difficult that not only algebra but even higher mathematics faltered. On the one hand, the methods of quantum mechanics were not well suited to describe an interaction as strong as the nuclear force. On the other hand, it became clear that pi-mesons alone could not ensure sufficiently tight binding between nucleons.

It seemed that meson theory of nuclear forces had reached its limits. Yet, in more recent years, new hope emerged. Excitement among theorists grew with the discovery, in accelerator experiments, of vector mesons — particles heavier than the pi-meson. These appeared to be the long-awaited partners of the pi-mesons, exchanged between nucleons at the very shortest distances. So far, a complete quantitative description of this exchange has not been achieved, but theorists continue their persistent efforts in this direction.

And the front line of nuclear physics kept stretching further. Research at particle accelerators was now being

complemented by experiments with heavy-ion accelerators. Laboratory results were compared with searches for superheavy nuclei in cosmic rays and on the ocean floor, as well as with astronomical observations of distant galaxies.

The need was not so much to predict new phenomena as to make sense of the ones already observed, and this need was pressing. All eyes turned to the theorists. People expected them to speak, to bring order, to see theory finally take up its duty. But time passed, and theory remained silent.

Physicists had laid the foundations of science at the microscopic scale with relativity, quantum mechanics, and other fundamental laws and principles. Upon this foundation, they were expected to construct a rigorous, mathematically consistent theory of the atomic nucleus.

Attempts to extend a seamless chain of analytic expressions—from general physical laws to the prediction of specific nuclear phenomena—proved unsuccessful. Many theorists, setting aside the dream of a fully respectable, all-encompassing theory, began to look for shorter routes to their goal.

Without delving into the actual mechanism of interaction between protons and neutrons, they instead sought mathematical formulas flexible enough—through the adjustment of numerous free parameters—to describe the behaviour of two nucleons and to calculate a range of nuclear properties with reasonable accuracy.

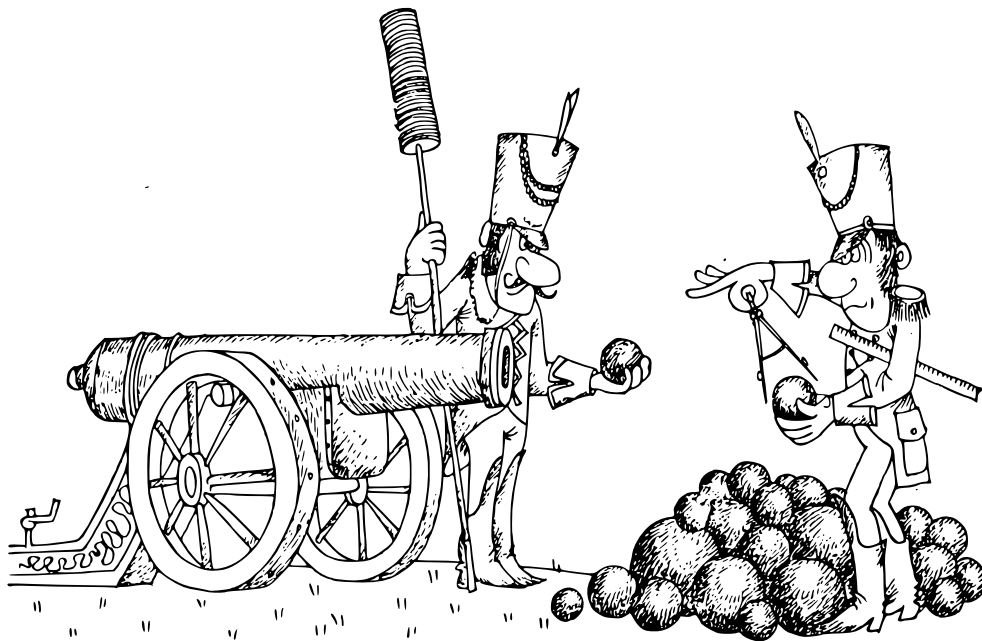
Another path, again bypassing strict theory, was taken by those who decided not to dig into the fine details of how protons and neutrons bind together inside the nucleus. Instead, they looked at the nucleus as a whole and treated it as a special kind of matter – *nuclear matter*. Their idea was to explain experimental results based on its broad, collective properties.

- Is it really sensible to speak of some special kind of nuclear matter, as if it had its own taste or colour?
- In a sense, all atomic nuclei are made from the very same “batch” of material.
- But nuclei are made of protons and neutrons; what has a “batch” got to do with it?
- And yet, one can imagine the nucleus as a particle of matter whose individual qualities do, in fact, resemble the familiar properties of the things around us.

It was the early experimenters who first proposed this view. They were the ones who had cracked open the atom and glimpsed its dense, mysterious core. At that time there were no specialists in nuclear theory. The pioneers worked on a do-it-yourself basis: whoever discovered a new phenomenon had to design the experiments to probe it, and then puzzle out the results on their own.

When physicists first discovered the atomic nucleus, they set about studying it with diligence. The obvious first step was to ask the simplest questions one could think of.

Their main tool was the alpha particle – the very first, and rather crude, probe of nuclear physics. With it they measured the electrical charge of nuclei. Then, since alpha particles have a knack for being drawn into nuclear attraction, physicists used them to estimate the actual size of the nucleus.



It soon became clear that not all nuclei could be the same size. A heavy uranium nucleus, for example, could hardly fit into the same tiny space as the nucleus of a light

element. Careful measurements across many different elements revealed a strikingly simple rule: the volume of any nucleus is proportional to the total number of nucleons – that is, the protons and neutrons it contains.

Of course, that dry and formal statement hardly conveys the stunning discovery hidden inside it. Put simply, it means this: in any nucleus, each proton and each neutron occupies the same amount of space.

In other words, one may speak of *nuclear matter* as a special material. It has no taste or smell, of course, but it does have one very tangible property – a constant density, just as ordinary matter does.

So nuclear matter is not a fiction, but a physical reality. Light nuclei and heavy nuclei are merely smaller or larger lumps of the same stuff, whose key feature – density – does not depend on the number of nucleons inside.

But then comes the deeper question: what actually turns protons and neutrons – the particles of nuclear matter – into a uniform substance with such peculiar properties? Do the nucleons themselves somehow change inside the nucleus, the way grains of flour become part of dough?

We do know this: a free neutron is unstable. Within about twelve minutes it decays into a proton, an electron, and a neutrino – that ghostly particle with neither charge nor mass at rest. Yet once trapped in nuclear matter, the neutron gains remarkable stability, living as long as the nearly immortal free proton. The reverse can also occur:

in certain radioactive nuclei, a proton transforms into a neutron, a positron, and a neutrino.

Still, the changes that protons and neutrons undergo inside a nucleus are not so radical that they alone can explain the unusual properties of nuclear matter. Flour becomes dough thanks to water and the vigorous hands of a baker. In the microworld, both of these roles are played by the nuclear forces. They are fully responsible for the “quality of the nuclear dough”.

While theorists argued endlessly over the exact mechanism of nuclear interaction – and over which particles carry it – experimentalists with the first powerful accelerators began uncovering the key “culinary” secrets of how nuclear matter is formed.

By firing accelerated protons at targets made of hydrogen and of deuterium (heavy hydrogen), physicists forced nucleons to “speak”. And in the language of scattering – the deflections seen when particles collide under various conditions – the nucleons revealed some of the inner workings of nuclear forces.

After painstaking analysis of vast amounts of data, scientists were able to pin down several crucial properties of these forces, which brought the still-blurry image of the atomic nucleus into sharper focus.

First: nuclear forces make no distinction between protons and neutrons; they bind any pair of nucleons equally well.

Second: unlike gravity and electromagnetism, nuclear forces have a peculiar property called saturation. Each nucleon interacts only with a few immediate neighbours and ignores all the others. The force sharply cuts off at a range of about 10^{-13} centimetres – much smaller than the size of a nucleus. This produces tightly bound clusters of nucleons.

Thus, by their very nature, nuclear forces “knead” the protons and neutrons into a tough, cohesive substance: nuclear matter.

Such an idea of the nucleus, based on the properties of nuclear matter known from numerous experiments, helped theorists to explain the results of nuclear reactions and even to predict new properties of nuclei.

It should be noted that scientists reached this idea by way of imagination, conjecture, and intuition. This path did not require the urgent mathematization of nuclear interaction. It was only necessary to guess what nuclear matter might resemble. To rephrase the words of the eminent French thinker Montesquieu, one could say that the task was to recognise the likeness of different things and the difference of similar ones.

- I cannot imagine how the nucleus, such a unique object as you claim, can resemble anything other than itself.
- Yet we have already established that it makes sense

to speak of the nucleus as a piece of matter with a definite density. Consequently, it is not at all surprising that one day it appeared to theorists to resemble, in some ways, an ordinary drop of water.

– Is that a joke?

– No. The grounds for such an analogy are not so few.

A nucleus imagined as a drop of nuclear matter and a drop of water are even outwardly similar. Most nuclei have a spherical or nearly spherical shape. But that shape is also energetically the most favourable for a drop of water: in this case its surface is minimal.

And let us look inside these systems! Water is an incompressible liquid with a definite density. The density is constant in nuclear matter too, which is also incompressible. A drop of water consists of a large number of individual molecules; a nucleus of protons and neutrons. The analogy extends in part also to the properties of the bonds between the internal elements of these very different systems. The chemical forces acting between molecules of water are the only ones in nature that possess the same property of saturation as nuclear forces.

Such facts, surely, cannot fail to convince even the most hardened sceptic. “But what is the use of all these comparisons?” he might ask.

And here is the point. The sole purpose of seeking something in common between the nucleus and a drop of

water was to use this analogy as a tool to calculate the mass of the nucleus, and to explain the results of nuclear reactions. That is, to get around the main deficiency of nuclear physics – ignorance of the law of nuclear interaction.

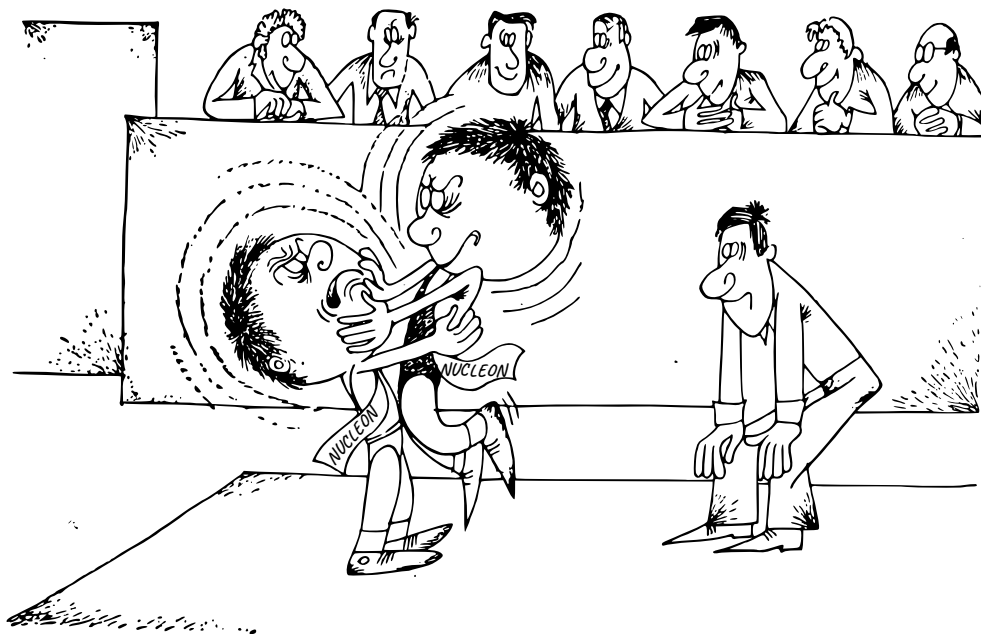
Once it was shown that the nucleus is analogous to a drop of water, it became possible to apply to it other features of this macro-object – and the most important of them, surface tension in a drop.

The water molecules forming the surface of a drop are pulled inward by the molecules beneath, and in this way they tighten the surface, creating a tension along it. Might the properties of the nucleus-as-drop also be described through surface tension?

And why not! This, after all, is the charm of the liquid-drop model of the nucleus.

Nuclear forces are short-ranged. Therefore, nucleons at the surface of the nucleus also feel attraction from the particles inside, and this too creates surface tension. Consequently, nuclear forces can quite naturally be pictured as a kind of surface tension within the nucleus-as-drop.

From the standpoint of the interactions between nucleons, the nucleus is a ring, where electrostatic repulsion and nuclear attraction are in constant combat. A stable nucleus is a ring where every round ends in victory for the forces of attraction.



In the theoretical picture of the nucleus-as-drop, surface tension stands against the electrostatic repulsion of the protons, which tries to tear the drop apart.

This formal replacement of nuclear forces by surface tension has no effect on the outcome of the contest — for the newcomer is, in essence, the same old participant in clever disguise. But physicists at once gained the ability to calculate, for example, the total energy of the nucleus. To the energy of proton repulsion they simply added the

energy of surface tension, which could be determined as straightforwardly as for a drop of water.

The mass of atomic nuclei, calculated from the energy using A. Einstein's formula, agreed quite well with experimental values.

This was the first major success of the theory — a reward for the insightful qualitative analogy between the atomic nucleus and a drop of liquid, despite the enormous difference in their nature.

The densities of nuclear matter and a drop of water are utterly incommensurable — nuclear matter is 10^{14} times denser!

The magnitudes of surface tension are no less incomparable. Stretch a soap film across a frame 10 centimetres wide, with a movable lower wire, and its surface tension will easily balance a small weight of one to one and a half grams. But the surface tension of a film made of nucleons, if such a thing could be stretched across the same frame, would balance a weight of no less than two hundred billion tonnes!

The first to recognise the similarity between such different "things" was the well-known theoretical physicist G. Gamow. He successfully used it to create the theory of radioactive alpha decay. However, the true triumph of this remarkable idea came with the explanation of the fission of uranium nuclei.

In the twenty-eight years that had passed since the dis-

covery of the nucleus, physicists had gained some experience in dealing with the microworld. So, when experimentalists working with accelerators encountered new nuclear reactions, they generally treated them calmly and without undue excitement. Why then did E. Fermi's early results on the absorption of thermal neutrons by uranium nuclei cause such a stir and so much agitation? Why was it so hard for scientists to bring themselves to say, "the uranium nucleus has split into two lighter ones?" The answer is simple: the new phenomenon contradicted the entire, albeit limited, experience of nuclear physics.

Two million electron volts were required to split such a loosely bound system as the nucleus of heavy hydrogen – deuterium – consisting of only one proton and one neutron. And in heavier nuclei, detaching a single particle demanded three or four times as much energy. The very first proton accelerator, launched in 1931 in E. Rutherford's laboratory, could accelerate particles only to one million electron volts.

With such a weak projectile, no one even dreamed of splitting very heavy nuclei, uranium included. And suddenly, with almost no expenditure of energy – "for free" – the uranium nucleus split in two, as if of its own accord. How could a single slow neutron, merely joining the 250 nucleons of a uranium nucleus, bring it to catastrophe?

The well-known Soviet theoretical physicist Yakov Frenkel, a scientist with a strong gift for using vivid imagery to describe physical phenomena, pointed out that the main

features of uranium fission can be understood once again by drawing an analogy with the behaviour of a drop of water.

There is a saying that a wagtail bird in spring breaks the ice on the river with its tail. Of course, when everything is already prepared for the ice to break up, even the wagtail can “help.”

A neutron absorbed by a uranium nucleus brings with it only about 8 million electron-volts of energy. This amount is tiny compared to the energy contained in the nucleus itself, but it disturbs the balance between two powerful forces – the electromagnetic repulsion and the nuclear attraction – and the round ends in victory for the repulsion.

Something similar to nuclear fission happens under certain conditions with a drop of water or any other incompressible liquid.

If a drop of water suspended in oil is slightly deformed, it will at first stretch a little, but then return to its original spherical shape. A stronger disturbance can stretch the drop so much that eventually it breaks apart into two. And the heavy uranium-235 nucleus never had an ideal spherical form to begin with. The victory of nuclear attraction was achieved only with great difficulty and was always on the verge of giving way to defeat. The 8 million electron-volts given to the nucleus by a thermal neutron acted like a blow to this nuclear drop, increasing its deformation. The drop elongated, and the electrostatic repulsion at its ends began to overcome the attractive forces. A constriction

formed in the nuclear drop, and the nucleus split into two parts.

The well-known Danish theoretical physicist Niels Bohr, together with his colleague John Wheeler, used the liquid-drop model of the nucleus to develop a theory of uranium fission. Armed with this model, the theorists even ventured to predict a new nuclear phenomenon. If a uranium nucleus splits in half merely because an additional neutron increases its deformation, then it should also be able to split on its own. Even a random rearrangement of the moving nucleons could be enough to cause the uranium nucleus to fall apart. And the prediction was confirmed!

The young Soviet physicists Konstantin Petrzhak and Georgy Flerov soon discovered that uranium nuclei are indeed capable of undergoing spontaneous fission.

The image of the nucleus as a drop of liquid captured the imagination of scientists. The first successes were inspiring, raising hopes that other properties of atomic nuclei might also be explained. But after some time, the weaknesses of the liquid-drop model began to reveal themselves.

- So, did physicists place too much trust in the resemblance of the nucleus to a drop of water?
- More precisely, the theorists tried to squeeze more out of the liquid-drop model than it could actually provide. For example, it turned out that this model

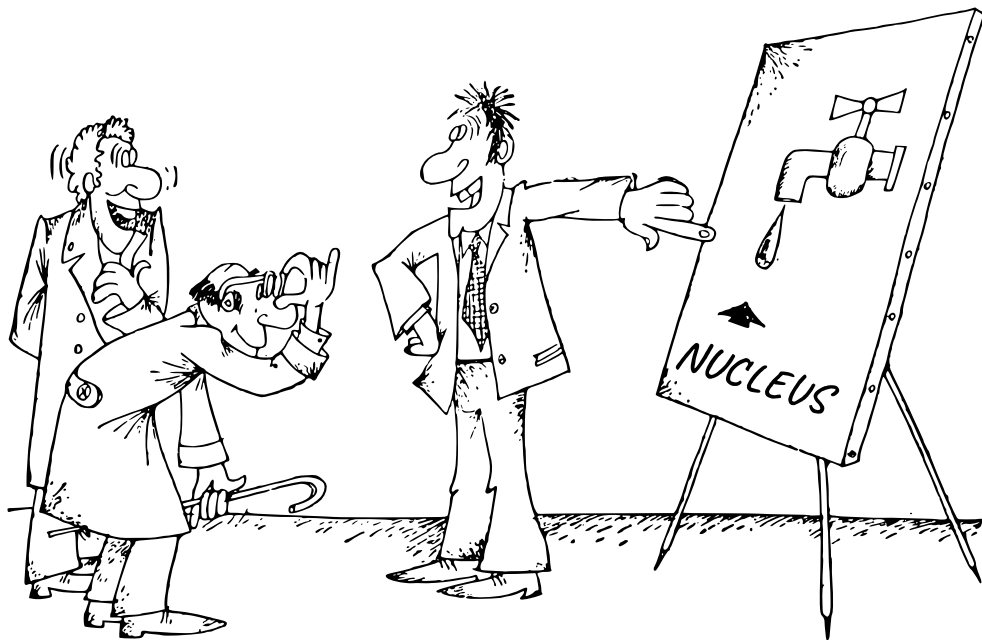
was unable to explain the so-called “magic” numbers of nucleons.

- Surely magic cannot play a role in the structure of nuclei?
- Experimenters discovered such properties of nuclei that allowed theorists to imagine them in ways completely different from a drop of nuclear matter.

Famous illusionists would have envied the rich ability of nuclear forces to confuse physicists. Yakov Frenkel once remarked that “ ... a theoretical physicist is like a caricaturist. A good theory of complex systems should amount to no more than a good ‘caricature’ of those systems, exaggerating the properties that are most typical of them ...”

The image of the nucleus as a drop of liquid suited these requirements perfectly. It seemed that nothing better could be devised. The liquid-drop model freed physicists from the tedious task of having to pin down the exact states of individual nucleons. One could simply forget about them – and about those troublesome nuclear forces.

This clever model made it possible to avoid thinking about the nucleus’s inner structure at all. After all, in incompressible nuclear matter of enormous density, with nucleons constantly colliding, the interactions between them had to be so intense that the very notion of “the state of a nucleon inside the nucleus” lost all meaning.



Yet every artist looks at the same subject in his own way. One and the same landscape can be transformed into completely different paintings. It was hardly to be expected that the nucleus would appear to all physicists in exactly the same light. Even though the first “caricature” of it was widely praised as remarkably accurate, some thought otherwise.

Only two years after the idea of the liquid-drop nucleus was introduced, the American physicist Bartlett offered his own sketch, his own vision of the nucleus. Unfortunately,

the timing was unlucky. The success of the drop model in explaining both alpha decay and the fission of uranium nuclei left the scientific community simply unable to take this new picture seriously.

Perhaps there was another obstacle too. In Bartlett's model, neutrons and protons were not spread uniformly throughout the nucleus. Instead, they were arranged in a particular order – grouped into special shells.

Such a construction of the nucleus seemed extremely artificial and far removed from reality, and Bartlett's model – later called the shell model – failed to win the hearts of physicists, neither in the first year nor in the second. Their loyalties belonged elsewhere ...

For sixteen years Bartlett's "caricature" was treated as a malicious cartoon, gathering dust on the shelves of the "storeroom". Yet, with time, more and more often experimenters found themselves turning back to it.

The reason was that from time to time they obtained results that could dampen the enthusiasm of even the most devoted admirers of the liquid-drop model.

Put five ten-kopeck coins in your pocket, and anyone can say you have fifty kopecks. By this familiar logic, it seemed natural to expect that both the magnetic and mechanical angular momenta of all nucleons in the nucleus should simply add up. But the calculations led to absurdities. The magnetic and mechanical angular momenta of atomic nuclei, as measured in experiments, had nothing

to do with the expected values.

Scientists had sincerely believed that the simple addition of nucleon angular momenta was consistent with the liquid-drop model. It turned out, however, that the question of the magnitude of a nucleus' mechanical and magnetic moments could not be resolved using that model.

It was then that Bartlett's "caricature" of the nucleus began to appear far more appealing to physicists than before. They began to consider: what if the difficulties in determining the magnetic and mechanical moments of nuclei were due to the fact that protons and neutrons do not lose their individuality within the nucleus? Perhaps it makes sense to speak of the state of an individual nucleon. Could it be that the nucleus has an internal structure, which causes the magnetic and mechanical moments of the nucleons to be oriented in a specific way relative to one another?

In the early 1950s, so many experimental facts had piled up that contradicted the liquid-drop model that it no longer seemed all-powerful. Physicists discovered that nuclei containing 2, 8, 20, 28, 50, 82, or 126 protons or neutrons – jokingly called *magic numbers* – had special properties. These nuclei were markedly more stable than others. The champions of stability were those with doubly magic numbers of nucleons. Examples include the isotopes helium-4 (two protons and two neutrons), oxygen-16 (eight and eight), lead-208 (82 protons and 126 neutrons), and a few others. Elements whose nuclei contained magic numbers of nucleons turned out to be especially common

in the solar system.

Most remarkable was the periodic change and repetition of certain properties among nuclei whose nucleon counts were close to the magic numbers. This naturally suggested an analogy between the internal structure of the nucleus and the structure of the atom itself.

The repetition of chemical properties in the periodic table is explained by the periodic filling of successive electron shells. Atoms with filled shells are the most chemically stable – for example, the noble gases. What if the magic numbers of nucleons correspond to filled nucleon shells inside atomic nuclei?

Without much hesitation, physicists triumphantly brought the shell model into the light of day – and were struck by how obvious its resemblance to reality was, leaving little room for doubt. Theorists immediately set about refining, polishing, and clarifying the main details of this idea of a shell structure of the nucleus. For their justification and deep development of this new view of the nucleus, the German physicists Maria Goeppert-Mayer and Hans Jensen were awarded the 1963 Nobel Prize in Physics.

In this model, protons and neutrons are thought to move in specific orbits within the nucleus. Whenever the number of nucleons matches a magic number, physicists assumed that a shell is filled at that point. This is how the “magicians” – the nuclear forces – reveal themselves.

But even here, physicists disguised nuclear forces in

the form of an averaged potential field, which governs the motion of the nucleons – much as the Sun’s gravitational field governs the planets, or the electromagnetic field of the nucleus governs the electrons in an atom.

This new picture of nucleon behaviour finally made it possible to calculate correctly, for the first time, the magnetic and mechanical moments of nuclei, as well as to explain several other properties.

The success led to the rehabilitation of the very idea of the “state of an individual nucleon” and confirmed that protons and neutrons in the nucleus move, to some extent, independently of one another.

But none of the authors of the various nuclear models ever hinted at abolishing the strong interaction between protons and neutrons. How, then, could one speak of nucleons moving in orbits inside an unimaginably dense nuclear substance?

This question, entirely reasonable when applied to macroscopic objects, turns out to be too simplistic – even misplaced – when it comes to the realm of the microscopic world.

The trouble is that our language has no concepts that adequately capture what happens inside nuclei. Phrases such as “strongly interact” or “do not interact”, which physicists use for a lack of something better, describe only certain aspects, snapshots torn from the peculiar quantum manner of behaviour characteristic of the microworld.

Of course, protons and neutrons do interact strongly with one another; otherwise, as is easy to see, they could never form the tightly bound system we call a nucleus. The liquid-drop model, which ignored the state of individual nucleons, consistently emphasised this feature of nuclear matter.

The shell model, on the other hand, assumes that the collective of nucleons exists in a once-and-for-all established realm of specific quantum relations. And the strict laws of this world – notably the Pauli principle – forbid even two identical particles from occupying the same state.

It turns into a kind of enchanted circle. On the one hand, nucleons must interact with each other – and strongly! – in order to form tightly bound, stable nuclei. On the other hand, nuclear protons and neutrons cannot really communicate with one another, because in any encounter “someone loses and someone gains” energy, and both particles involved must inevitably shift to different quantum states. But which ones? In the nucleus, the only vacant spots lie on the upper shells, while the deeper orbits with lower energies are never empty. So where should a particle go if, in a collision, it loses energy and ends up the ‘loser’?

Thus, physicists are forced to regard protons and neutrons as independent. Condemned, thanks to the clever disguise of nuclear forces, to a kind of loneliness in the dense crowd of their own kind, nucleons nonetheless gain the right to move for long stretches along their individual orbits.

In fact, these two seemingly different pictures of the nucleus are not contradictory. The nucleus as a drop of nuclear matter, and the idea of a shell structure, each highlight genuine but opposite aspects of the behaviour of this unique system of elementary particles.

– Not a nucleus, more like a two-faced Janus! – Alas, the tiny heart of the atom resembles rather a “man with a thousand faces”. – And how do physicists make sense of all these “faces”? – Theoreticians, like skilled fashion designers, select – and if none fit, create – new models for atomic nuclei.

In each specific nuclear reaction, the atomic nucleus seems to reveal only one of its sides. Heavy nuclei behave as if they were drops of viscous, incompressible liquid, while lighter ones show the independence of their nucleons. Yet a deeper, more detailed study of nuclear reactions overturns this superficial impression. In the drop-like nucleus, traits shaped by the shell structure often come to the fore. And conversely, supposedly independent nucleons participate in collective motions.

A theoretical picture of the nucleus had to capture the unity of these two opposite features, just as experimenters had uncovered.

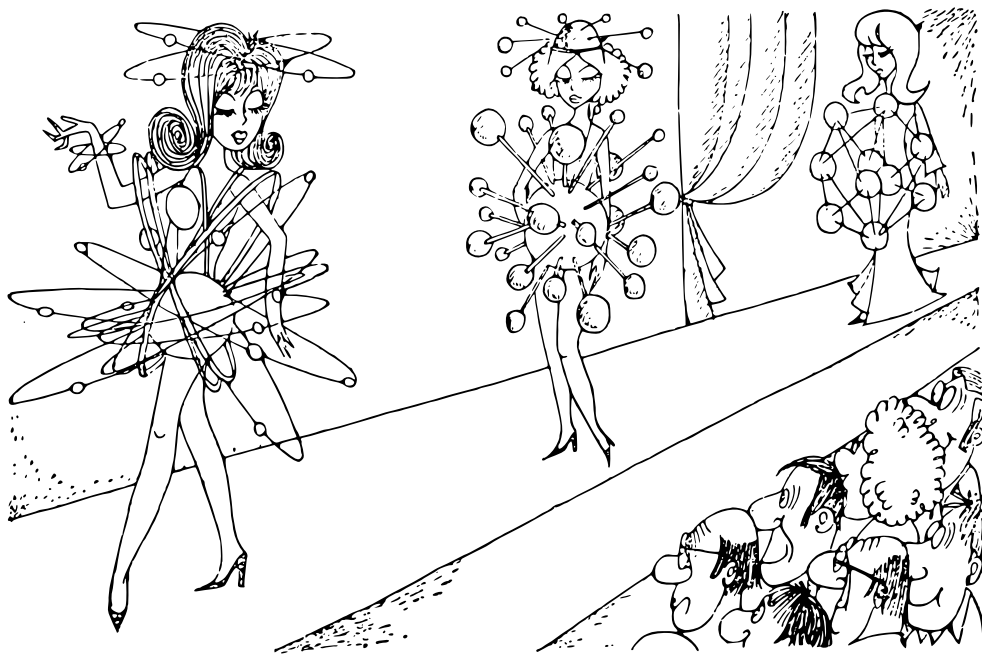
It seems as difficult as trying to see a person both full-face and in profile at once. Yet the portraits of the Italian painter Amedeo Modigliani convince us that it is possible.

And to explain the departure of heavy nuclei from a perfectly spherical form, physicists succeeded in creating a new, unified model of the atomic nucleus – a successful synthesis of the liquid-drop and shell models.

We have already noted that deformation noticeably alters the balance of forces within the nucleus. To detect, and still more to calculate accurately, the degree of distortion – an effect that consumes only a few thousandths of the nucleus's total energy – is as hard as spotting traces of former slimness in the figure of someone who has put on weight. Nevertheless, the shell model allows one to determine how much the nucleus's shape is distorted by nucleons moving in the outer, unfilled shell, pressing unevenly on its surface. The liquid-drop model, on the other hand, accounts for the volume and surface oscillations of nuclear matter produced by the collective action of all the tightly bound nucleons together.

Nuclei with completely filled shells have a perfectly spherical “shape” and know nothing of deformation. But for most nuclei that are not very light, their form is far from ideal. How then can we connect the deformation caused by the influence of outer nucleons with the collective oscillations of all the other protons and neutrons?

One may imagine any heavy nucleus as consisting of two inseparable parts. One part is a spherical drop with filled shells, and the other is a handful of nucleons on the outer, unfilled shell.



The more the number of these outer particles differs from the nearest magic number, the greater the distortion they produce on the surface of the drop. This deformation immediately affects the condition of the outer protons and neutrons, because it alters the average field of forces generated by all the nucleons in the drop.

Thus, for the first time, it became possible to link the properties of individual neutrons and protons with their collective motions inside the nucleus. And at once, many

experimental results found their explanation. In particular, it turned out that the order in which shells are filled in heavy nuclei depends on the state of the entire nucleon system as a whole.

The generalised model of atomic nuclei still enjoys great popularity among theorists today. For its creation, quite recently in 1975, J. Rainwater, A. Bohr, and B. Mottelson were awarded the Nobel Prize.

But the nucleus — this astonishingly many-faced object of the microworld — often reveals itself from such unusual sides that even this model cannot account for every nuance of its behaviour. Theorists have therefore been compelled to create endless variations of already known models, taking into account additional interactions between nucleons, and to seek ever new approaches to explain curious experimental facts. For example, the nucleus is compared with different macroscopic systems — not only with such familiar ones as liquids, gases, or crystals, but even with the exotic state of matter in which helium exists at ultra-low temperatures.

For more than sixty years, physicists have been carefully studying the “faces” of atomic nuclei. Yet to this day, no single portrait has managed to capture the full character of this elusive subject for the artist-theorist. A unified theory of the nucleus still does not exist.

Professor Ya. Smorodinsky said that “the nucleus represents a very complex system, one with which we will still have to struggle considerably before even the basic

patterns become clear.”

Meanwhile, until these patterns are clarified, researchers are forced to use a broad array of approximate representations of nuclei. In this sense, as one physicist wittily remarked, the Temple of Science could just as well be called the House of Models.

Today, a qualitative explanation within the framework of a particular model can account for almost all facts obtained by experimenters, but establishing quantitative relationships succeeds rather rarely. And even then, these numbers often tell us little. According to the theorists themselves, a well-chosen formula with five parameters can always describe fifty arbitrarily chosen numbers with five-percent accuracy. Today, theory mainly explains what experiments do, rarely interprets results correctly, and even more rarely ventures predictions. Experiment remains the leader in nuclear physics.

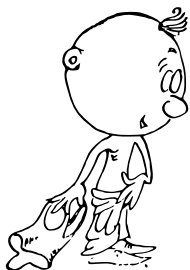
Some theorists, however, hope that once the forces acting between two nucleons are correctly determined, it will be possible to describe all the properties of nuclear matter.

However, it may turn out that fulfilling this condition regarding nuclear forces will be insufficient to solve the entire problem of the atomic nucleus. After all, the properties of even the simplest cell could not be recreated solely on the basis of the laws of molecular biology!

Others believe that an exact description of the interac-

tion between two nucleons, especially at very short distances, is fundamentally impossible, and they find confirmation of this in experiments on proton scattering from protons and neutrons.

Well, the situation is entirely scientific, for, as the famous Soviet physicist P. Kapitsa said: "Where doubts end, science ends."



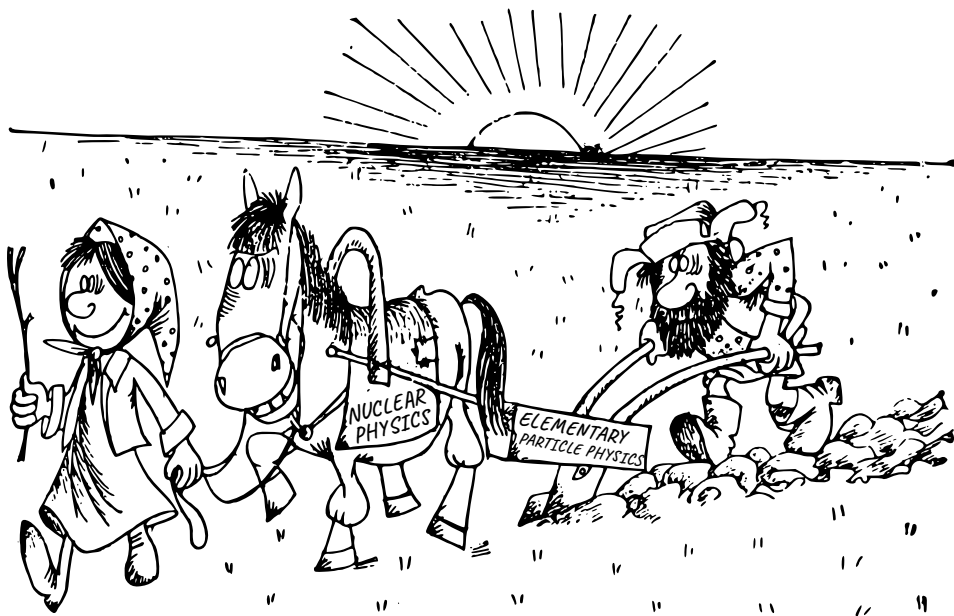
JOURNEYS INTO THE HEART OF THE NUCLEUS



3 Journeys Into the Heart of the Nucleus

- From what you have told me, it seems physicists rather easily managed to make contact with the nucleus.
- It depends on what you mean by contact. As early as Rutherford's experiments, his colleagues were already dealing with the nucleus when they transformed nitrogen into oxygen.
- But that kind of contact was purely accidental. I am curious how scientists later figured out what the nucleus actually is and what methods are needed to study it.
- The history of scientists' "relationship" with the atomic nucleus resembles the story told in S. Lem's novel about humanity's attempts to contact the planet Solaris; there were periods of excitement followed by

decline, disappointments alternating with fresh hopes.



The unexpected discovery of the atom's treasure vault – the atomic nucleus, almost point-like in size – aroused enormous interest in this tiny spot of space. Yet even over the next twenty years, scientists did not manage to learn very much about the riches stored within it. The information gathered by experimenters boiled down mainly to the fact that nuclei are made up of protons and neutrons, and that the behaviour of nuclei and some of their properties

depend on the number of these particles.

But the main secret of this complex system – the nature of nuclear forces – remained out of reach. Before scientists stood, in all its immense complexity, the problem of describing these forces.

The limited and discouraging conclusions could have cooled the ardour of more than one enthusiast of nuclear physics. But the most persistent did not give up and continued to accumulate information about this “Solaris” of the microcosm.

The information was obtained mainly not by active intrusion with the help of some micro-instruments into the depths of nuclear matter, but rather by observing those properties that manifested themselves in radioactive decay of nuclei or in those nuclear reactions where it was possible to stir the nucleons slightly.

Many believed that nuclear physics had reached an impasse. And this seemed close to the truth.

The study of the elementary particles themselves, from which the atomic nucleus was composed, appeared much more interesting and promising.

About thirty years ago, as soon as the first high-energy proton accelerators appeared, scientists managed to discover certain properties of nuclear forces manifested in the interaction of a pair of protons or of a proton with a neutron. But this, in essence, was the extent of the contribution of the “particle physicists” to nuclear physics at that

time.

Observations of high-energy nucleon collisions brought new and unexpected discoveries, and the experimenters, carried away by the study of these building blocks of the nucleus, suddenly realised that they had long since left the nuclear domain and were already wandering in the world of elementary particles. But by then it was too late to stop. They had acquired the most powerful accelerators, mastered the art of creating beams of protons, neutrons, and such secondary unstable particles as pi- and mu-mesons, heavy K-mesons, hyperons, and had accumulated invaluable information about these representatives of the microworld.

Yet even the entire body of this extremely important knowledge proved insufficient for understanding how nucleons behave in a collective.

Gradually, the idea crystallised that no new insights into nuclear forces and the internal structure of the nucleus could be gained from outside — they had to be obtained within the nucleus itself. Reflections on the properties of nuclear matter led to the same thought. If the nucleus were like a box filled with balls of two colours, it would be enough to know how many balls of each colour it contained, and one could then claim to know its internal structure. But the nucleus is a far more complex system of neutral and charged particles, endlessly interacting with each other — a system constantly striving to expand under the electrostatic repulsion of protons, yet pulled almost to

a point by powerful nuclear attraction. For such a system, the concept of “structure” turned out to be far deeper than for a box of balls.

It is impossible to understand the structure of the dense nuclear cluster of nucleons without knowing, for example, how electric charges are distributed within it and how nuclear matter as a whole is distributed in space. Physicists became convinced that no matter how much they studied collisions of any pairs of nucleons, they would never obtain answers to these questions. It was necessary once again, with even greater precision, to measure the basic parameters of the nucleus: its size, shape, the distribution of charged protons and neutrons within it – literally everything that reveals its structure and bears the imprint of the qualities of the chief organiser of the nuclear collective of nucleons – the nuclear forces.

The once deserted observation posts around the “Solaris” of the microcosm again filled with advocates of closer contact with the ocean of nuclear matter. But this time, alongside nuclear physicists stood particle physicists, who did not come empty-handed – they offered fundamentally new methods of penetrating into the world of nuclei.

The leading positions in the study of elementary particles shifted to the world’s largest accelerators. Therefore, in different countries, scientists at institutes that had previously studied only elementary particles began to use their entire powerful arsenal of experimental tools for the investigation of atomic nuclei.

The narrow border zone between the old nuclear physics and the young physics of high energies began to turn into a fruitful field of science, expanding with each passing year.

The official establishment of this collaboration took place in 1963. On the initiative of theoretical physicists V. Weisskopf and T. Erikson, scientists gathered at the European Centre for Nuclear Research in Geneva for the first International Conference on High-Energy Physics and Nuclear Structure.

Since then, every two years physicists have met to discuss together their latest achievements in this field of microcosmic research, taking turns in the Soviet Union, Western Europe, and the United States.

Several years ago, the fourth such “review” of the combined forces of particle physicists and nuclear physicists was held in the Moscow-region town of Dubna — the centre of nuclear research for scientists of the socialist countries. More than three hundred representatives of many laboratories around the world assembled there. Among those who came were well-known scientists, for example Professor Wu Chien-Shiung from the United States, who through her experiments was the first to prove that the law of conservation of parity (one of the most important laws of quantum mechanics) is violated in the world of elementary particles.

Speaking before her colleagues, she said that the gap between high-energy physics and nuclear physics had already been eliminated, and that scientists working in these

once sharply separated fields of microcosmic research now understood one another perfectly well.

Her words were confirmed by the breadth of the topics addressed at the conference, the great interest in all the presentations, and, of course, the lively debates. These took place not only during the sessions, but also in the intervals between them, in the foyer, over a cup of tea or coffee. Here and there, small groups and pairs formed, continuing the discussions that had begun in the hall.

There was no shortage of material for discussion. Having brought into play for the study of atomic nuclei almost all the elementary particles obtainable with the help of accelerators, experimenters saw the nucleus in a completely new light.

- What new things about the nucleus did they learn?
- It astonished them with effects no less complex than the thinking ocean of Solaris – or the pilot Burton. It is by no means simple to interpret what the experimenters observed in the nucleus.
- Does that not mean that they too are not entirely believed?
- Strictly established experimental facts cannot be disbelieved. Even a single correctly understood fact – the constancy of the speed of light, as you may recall – pointed to the true place of all classical physics. The matter is different: however good each method of studying the atomic nucleus may be in its own way, it

is also limited in its own way.

It is well known that all news of the invisible microcosm reaches experimenters, so to speak, “second hand.” Therefore, the objectivity and significance of experimental results are linked to the capabilities of the probes and detectors that come into direct contact with the atomic nucleus, for example.

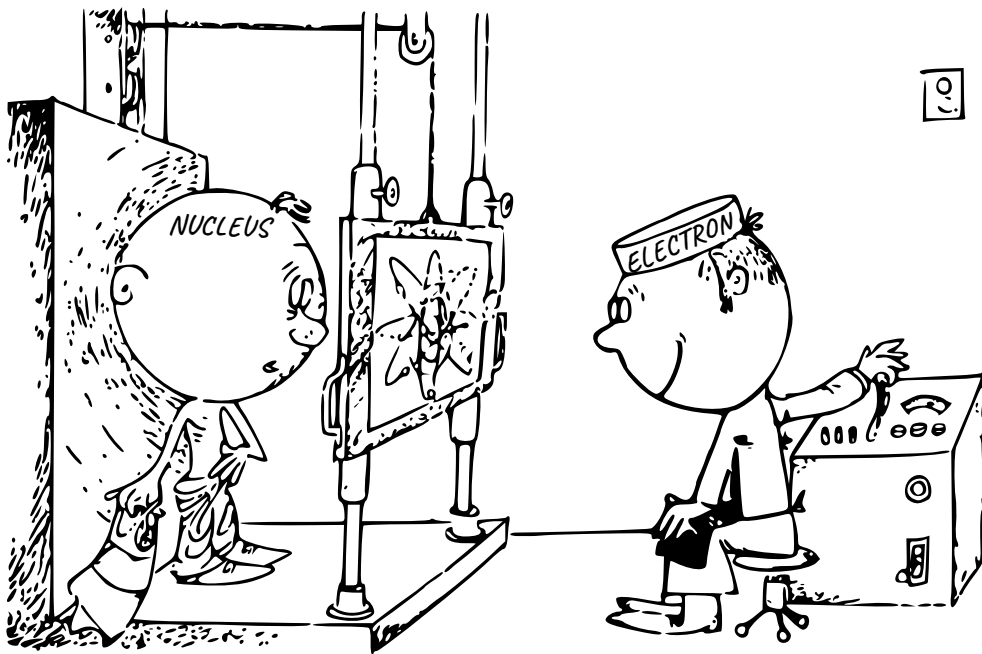
The acuity of any intra-atomic instrument depends entirely on the wavelength that corresponds to it according to quantum mechanics. Objects smaller than this main working part of the instrument are indistinguishable to it. It was possible to detect atomic nuclei with the help of alpha particles precisely because these particles had a wavelength that coincided with the size of the nucleus.

But to look inside nuclei one needs such special probes as electrons with energies of tens of billions of electron volts, whose wavelength is comparable to that of nucleons. They can see “through” not only atomic nuclei but even elementary particles.

Nevertheless, even the reserve of acuity possessed by these electrons does not make their judgement about nuclear structure entirely objective.

The more talented the director, the more persistently he seeks in each play or film script the theme that interests him, rather than striving for cold impartiality in staging. The sole and constant theme of electrons is electromag-

netic interaction. They find only charged protons in nuclei and scarcely notice the neutrons. As a result, physicists form an impression of the atomic nucleus that is original but somewhat one-sided.



And even with such a biased approach, the nuclear drop lost those features of ideality that experimenters had attributed to it when interpreting data obtained from alpha particles that could barely discern the nucleus, and acquired a more reliable appearance.

It turned out that the nucleus has no sharply defined boundary. The closer to the surface, the more rarefied the nuclear matter becomes. The nuclear radius is taken as the distance at which the density of nuclear matter decreases by half.

Passing through the nucleus at a speed close to the speed of light, an electron manages, via electromagnetic interaction, to probe the spatial distribution of protons in the nucleus, so to speak, by the lateral force it experiences – that is, by the angle of deflection from its original trajectory.

The “sides” of electrons turned out to be so sensitive that nuclear radii could be measured with an accuracy of up to one percent, and relative changes in nuclear size – even to one hundredth of a percent!

And it was then that the slight influence of subtle nuances in the infinite duel between electrostatic repulsion and nuclear attraction became clearly visible. Of two nuclei with the same number of nucleons, the one with more protons had a larger radius of charge distribution.

Here is a vivid confirmation of how electrostatic forces (also called Coulomb forces), acting between charges of the same sign, “push” protons toward the surface.

But how are charged particles distributed throughout the bulk of nuclear matter?

In the conception of nuclear structure that had formed after experiments with low-energy electrons, the charge

density in the inner part of atomic nuclei was always treated as a constant value. In textbooks it was depicted as a smooth, straight line dropping steeply near the nuclear boundary. Fast electrons immediately exposed this idealisation of reality. As soon as scientists, from new experimental results on electron scattering, calculated the charge density at different depths of nuclear matter, they obtained not a straight line but a curve with clearly expressed rises and falls.

The experimenters had done their part – they had set the theorists a problem. Theorists now had to provide an interpretation of this most important fact: the discovered non-uniformity in the density distribution of electric charges in the atomic nucleus.

At first, its interpretation caused no difficulties. Everyone unanimously acknowledged that, apparently, this was a manifestation of the shell structure of nuclei. But more recently, the voices of theorists proposing a different hypothesis have been sounding with growing confidence. They believe that electrons have helped uncover an entirely new layer of nuclear properties. What is it?

The Soviet theoretical physicist, Academician of the USSR Academy of Sciences A. Migdal, suggests that the non-uniformity of charge distribution may be connected with the existence in the nucleus of regions with increased density of nuclear matter, having no relation to nucleon shells.

It turns out as though nucleons are “torn apart”, being

simultaneously members of different communities. Well, such a situation is quite common in the macroworld, when one and the same person is a member of a trade union, a philatelic society, and, for example, an association of aquarium fish enthusiasts. Perhaps this is also the norm of behaviour in the microworld?

One property of nuclear forces has long been observed: they depend on how the angular momenta of the interacting particles are oriented. It is possible that nuclear forces create from specially oriented protons and neutrons an entirely separate layered spatial structure. In these condensed layers nucleons approach one another at distances smaller than those usually permitted by the rules of social behaviour in the nucleus. In this case, naturally, the density of the pi-mesons with which they exchange should increase sharply. This hypothesised condensation of pi-mesons has been given the name “pi-meson condensate”.

Theory so far says nothing about how stable in time the formation of a “pi-meson condensate” may be; nevertheless, this new approach to the internal structure of nuclei is extremely interesting.

When reasoning about the structure of nuclear matter, physicists usually spoke of protons and neutrons, of their spatial distribution, and finally of nuclear forces, but they assigned no role in the structure of the nucleus to the pi-mesons that arise and immediately vanish — the agents of internucleon exchange.

It is quite possible that the picture of a nucleus con-

sisting only of protons and neutrons resembles the real nucleus no more than a prepared specimen of a cell under a microscope resembles a living cell.

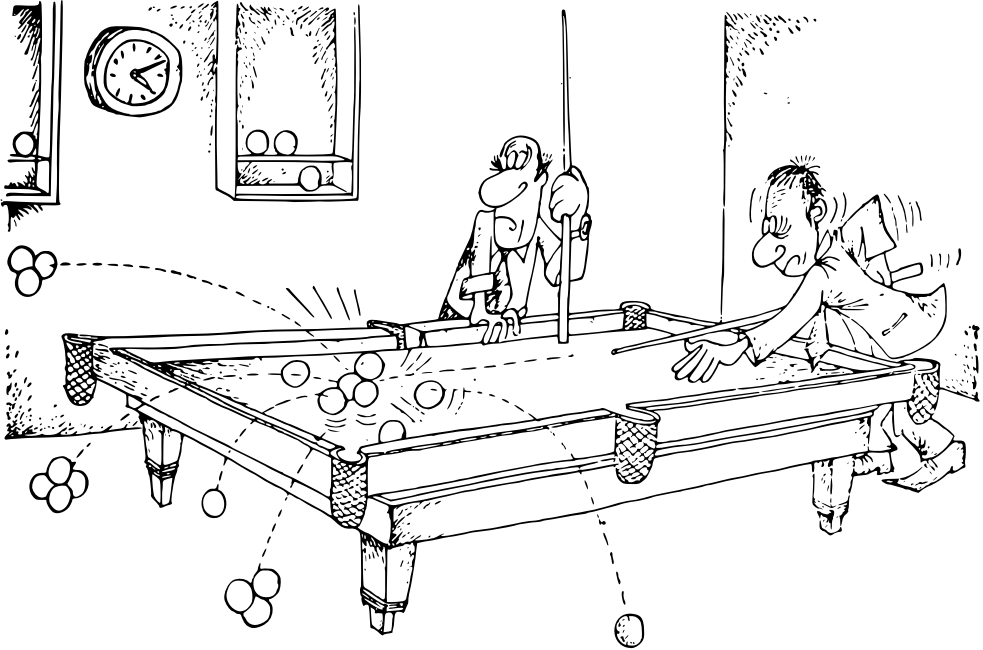
Theorists propose to conduct special experiments to search for a “pi-meson condensate”. A. Migdal believes that it could be detected, for example, by scattering high-energy electrons on nuclei with pre-oriented angular momenta.

Great interest among experimenters was aroused by the suggestion of the Swedish theoretical physicist T. Erikson: to attempt to register the reaction between negatively charged pi-mesons entering nuclei and the pi-mesons belonging to the nuclear structure.

Undoubtedly, electrons have revealed many interesting features in nuclear matter, and new experiments with them may perhaps bring even more important information about the nucleus, although such information will always suffer from the one-sidedness already familiar to us.

- A complicated situation. You cannot force electrons to look at the nucleus “with different eyes”. So it seems one has to put up with this limitation?
- Of course, the electrons did all they could. Therefore the experimenters began sending new observers into the nucleus.
- Obviously, these were particles in some essential respect completely unlike electrons?

– This time the physicists employed strongly interacting particles — protons with high energy. It was they who helped to reveal remarkable peculiarities in the behaviour of nuclear nucleons.



From the new “specialists” on the nucleus no one expected sensational information about the spatial distribution of nuclear matter, although they did possess far greater possibilities than electrons.

In experiments with fast electrons it was possible to probe quite well the distribution of protons in nuclei. It was assumed that neutrons were arranged in a similar way, since they are bound to protons by nuclear attractive forces. And the physicists very much wished to obtain from the new scouts – fast protons – direct confirmation of this assumption. But the principal advantage of accelerated protons – viewing the nucleus through the prism of strong nuclear interaction – was not realised immediately.

At first, the main theme sounded very uncertain. The form given to it by the experimenters was unsuccessful: the scattering of protons on nuclei. Protons spoke of everything they observed much less intelligibly than electrons. In general, the results did not contradict what was already known. But in detail it was impossible to understand because of the lack of knowledge about the laws of nuclear interaction. And this most important tool of research in particle physics – high-energy protons – for some time was used only in an auxiliary role in the study of atomic nuclei. This continued until the experimenters found for protons the genre in which their main theme – the strong interaction – played in full force.

Nuclear matter is to the greatest extent “transparent” to protons with energies from 500 to 700 million electron volts. They penetrate to any depth of it, clearly distinguish individual particles, and enter into nuclear reactions with them. Not scattering, but direct interaction with an individual nuclear proton, transferring energy only to it – this was the type of reaction that turned fast protons into a

special, indispensable probe of nuclear structure. Physicists denote reactions of this kind with the symbol “ $p; 2p$ ”, which means: an accelerated proton strikes the nucleus and knocks another proton out of it. As a result, two protons leave the nucleus.

But not every proton knocked out of the nucleus can tell us something interesting about the order that reigns inside it, for example, about its shell structure. If the incoming projectile proton interacts with the nucleus as a whole, then the outgoing proton becomes hopelessly depersonalised. It no longer carries information about which state, and with what energy, it occupied in the nucleus.

What interests the experimenters is a reaction in which the projectile proton transfers its energy directly to one of the nuclear protons. In this case, the nucleus itself in no way interferes in the division of energy between the two nucleons. By recording the energy of the two protons leaving the nucleus, both simultaneously striking the detectors, and the angle of their separation, physicists can easily calculate what energy the nuclear proton had before the collision.

Fifteen years of intensive work bore fruit – the experimenters obtained the spatial distribution of protons in different nuclear shells for many atomic nuclei.

In the “ $p; 2p$ ” reaction, scientists even succeeded in measuring the energy required for the “nuclear ionisation” of each shell – that is, for pulling a proton out of it.

The arrangement of all nucleons within the collective called “shells” was finally established with complete certainty. The results of the experiments fully confirmed the calculations carried out using this model. The radius of the nucleus, obtained by summing the distribution of protons across all shells, coincided within one percent with the value measured in experiments on elastic electron scattering.

But the experimenters did not turn a blind eye to other circumstances either. Quite often, a fast proton transferred part of its energy not to a single proton, but knocked out from the nucleus an entire group of tightly bound nucleons – a *cluster*, as physicists call it.

Just as the pilot Burton observed clumps resembling earthly objects in the depths of Solaris’s ocean, physicists, with the help of protons, discovered in nuclear matter various short-lived condensations of nucleons.

By chance approaching each other, a proton and a neutron sometimes form a clump resembling the nucleus of the hydrogen isotope – deuterium; and two neutrons together with two protons briefly stick together into a lump resembling an alpha particle – the nucleus of helium-4. These temporary formations differ from ordinary nuclei of the same type only by their very small size.

This dynamic, cluster-like structure of the nucleus is nothing other than the emergence of ultra-dense lumps of nucleons within comparatively homogeneous nuclear matter.

In poorly cooked jelly, dense lumps can quite well be considered indirect evidence that the dish could have been made thicker.

And could nuclear matter, in principle, also be made denser?

It would seem that it could. The nuclear forces of attraction are capable of making all nuclear particles collapse, compressing into one super-dense lump of a size on the order of their range of action. However, nucleons only rarely realise this possibility, forming clusters. Scientists explain this very interesting and important fact, in particular, by noting that at very short distances – approximately equal to half the range of attraction – nucleons begin to repel each other with enormous force.

This idea was first expressed already in the late 1930s and 1940s. At that time, it received very little attention, since scientists believed it contradicted the notion of a simple structure of the elementary particle. But when that notion dispersed “like smoke, like morning mist”, and physicists, shaken by their discoveries, were forced even to abandon the use of the epithet “elementary” – first of all with respect to protons and neutrons – the idea of repulsion between them at short distances gained the right of citizenship. This hypothesis was also supported by the results of experiments on proton-proton scattering.

Thus, the density of nuclear matter is not arbitrarily set by nature, but is the result of a dynamic equilibrium between the forces of attraction, as if hoops tightening

the entire system of nucleons, and resistance from within, which prevents any further reduction of volume.

All the more interesting, therefore, are cases where this ordinary state of nuclear matter is disturbed – the appearance of super-dense clumps of nucleons. They provide direct information about the behaviour of protons and neutrons at ultra-short distances, where, apparently, forces of repulsion between particles even more powerful than attraction come into play. At present, there is no other way to obtain comparable information.

In nuclear clusters, nucleons approach one another, so to speak, voluntarily. But the enormous energy required to bring free nucleons close enough to a distance comparable with the range of repulsion leads to the birth of many new particles. And the moment of such convergence is accompanied by so many extraneous phenomena that it becomes practically impossible to get to the bottom of the properties of nuclear forces.

Turning the reaction of knocking out clusters with high-energy protons into an instrument for studying the structure of the nucleus and the nature of nuclear forces was, to a great extent, the achievement of the scientists of the Laboratory of Nuclear Problems at the Joint Institute for Nuclear Research in Dubna.

– Yes, studying the nucleus with particles rushing through it at the speed of light must be rather trouble-

some. But is there not some calmer way of doing this?
— Such a possibility appeared only after the discovery of special, short-lived atoms unlike the ordinary ones. — What, do the nuclei in such atoms reveal their secrets by themselves? — No, scientists study the nucleon collective with the help of particles — “nucleowalkers” — which make a soft landing on the nucleus and even penetrate into its depths for a time.

The role of a “nucleus-walker” was assigned to a light elementary particle with a single negative electric charge — the mu-meson. For the 40 years that have passed since scientists first became acquainted with this particle, it has not been possible to discover its special talent, to understand in what lies its uniqueness, and why it is needed at all in the microworld.

Malicious tongues claim that there is nothing original in it; that it is simply an electron with a mass 210 times greater. This, of course, is hard to believe. “Nothing happens without sufficient reason,” wrote M. Lomonosov. And science at every step confirms these words. But, evidently, in the case of the mu-meson these “reasons” lie quite deep, and they are not so easy to reach. And while theoreticians continue their attempts to “crack” the mu-meson, experimenters have long used it in episodic, “passing” roles in the study of the microworld. The role of the “nucleus-walker” is one of the most serious.



Professor Wu Jianxiong at a conference in Dubna said that, having lost their novelty for particle physics, mu-mesons have acquired great importance as a tool for studying atomic nuclei. This curious tool arises at the end of a chain of nuclear reactions, following one after another. First, protons, accelerated in a powerful accelerator, strike a piece of matter – a target – with full force and generate new particles, pi-mesons. And pi-mesons, in turn, decay into lighter mu-mesons.

But a mu-meson by itself is not yet a tool. It becomes a “nucleus-walker” only after it forms an unusual, *exotic atom*. The words “exotic atom” sound rather strange at first glance. What kind of exoticism can there be in atoms, all the nooks and crannies of which have long been explored and re-explored?

In our time even schoolchildren know that atoms consist of electrons, neutrons, and protons. The structure of atoms is indeed understood so well that physicists are capable, at will, both of destroying them and of creating new ones.

The first artificially created exotic atom was the lightest atom of *positronium*. Theorists began to speak seriously about it immediately after the discovery in 1934 of the electron with a positive electric charge – the *positron*. The neutral atom of positronium, like all atoms, in which one electron was to orbit around the positron, seemed so real that it received its chemical symbol even before being discovered experimentally in 1951.

For more than a quarter of a century scientists have been working with various artificial atoms, and have become so accustomed to this short-lived exoticism (the positron lives for millionths of a second) that sometimes ordinary natural atoms appear to them as derivatives of these ephemeral ones.

The novelty of the exotic mu-mesoatom lies in the fact that, in addition to electrons, protons, and neutrons, it also contains a mu-meson. The negatively charged meson is a

welcome guest of the atom – more precisely, of the nucleus. It is the nucleus, with its large positive electric charge, that attracts the mu-meson, stopped in the substance, like a magnet.

Unable to resist the insistent invitation, the meson settles on one of the outermost electron orbits, far from the nucleus. Yet the guest's position does not release it from obeying the quantum laws at work in the atom. "The radius of a near-nuclear orbit of any particle is inversely proportional to its mass" – this rule dictates. It commands the meson to seek its place on orbits about 200 times closer to the nucleus than the electronic ones.

There is nothing to be done – one cannot go against quantum mechanics; the meson is forced into a steep dive. Jumping from orbit to orbit, it rapidly approaches the centre of the atomic planetary system, the nucleus.

In atoms of medium-mass chemical elements, the mu-meson, being on the innermost orbit, literally grazes the surface of the nucleus. In a lead atom, it not only makes a soft landing on the nucleus but even plunges deeply into the nuclear matter.

It has already been said that in the microcosm all events take place on extremely compressed timescales. And the mu-meson – the "nuclear walker" – exists for far less than a second. Yet by nuclear standards, this is an eternity. Engulfed in the depths of the dense nuclear ocean, the mu-meson, before disappearing in a reaction with a proton, manages to make millions upon millions of revolutions.

How is it that mu-mesons manage to penetrate so freely into the nucleus and move about there without losing their individuality? The reason again lies in quantum laws. They state that penetrability or impenetrability in the micro-world does not depend on the hardness or softness of a barrier, as we are used to thinking, but on the presence or absence of vacant places in certain quantum states.

A bullet cannot pierce thick armour, and we say that it is impenetrable. But if the bullet were suddenly to turn into a quantum object, it would easily penetrate it, because in that case all quantum states in the armour would be free for the bullet. Likewise, for the mu-meson all the states in nuclear matter are free. Moving about easily within it, the mu-meson “unhurriedly”, in calm conditions, records the shape of the nucleus, its size, and the spatial distribution of protons in it, and transmits all this information to scientists through the channel of meso-*X*-ray communication”.

This “channel” works continuously from the moment of the formation of a mu-mesoatom until the meson is captured by the nucleus. Jumping from one of its orbits to another, located deeper in the atom, the meson, in accordance with quantum laws, emits *X*-radiation. Physicists call it meso-*X*-radiation, to make it clear to whom it owes its origin.

The mu-meson, like the electron, is not subject to the strong interaction. Its contact with the nucleus is mainly limited to electromagnetic and weak interactions. And the closer it comes to the centre of the atom, the stronger the

influence of the nuclear cluster of electric charges upon it becomes.

The meso- X -ray photons, which the mu-meson emits when jumping between the deepest final orbits, carry with them the full wealth of its electromagnetic “impressions” of the nucleus. It is very important to be able to “extract” these impressions from only two experimentally measurable characteristics of the X -radiation: its energy and its intensity.

Here is how, for example, the theoretical dependence of the energy of this radiation on the size of the nucleus is obtained, in the playful account of the physicists themselves.

First, the theorist imagines the nucleus as a kind of charged cloud. And not only in his mind, but also on paper, in mathematical form. Similarly, the mu-meson moving within the nucleus is presented as a smeared, jelly-like object. And when this cloud and jelly, seasoned with such “spices” as relativity theory and spin (the mechanical angular momentum), are “poured” into an electronic calculating machine, the long-awaited result pops out: the dependence of the energy of X -rays on the radius of the nucleus.

The very first experiments with meso-atoms, carried out a quarter of a century ago, made an extraordinarily important contribution to nuclear physics. From the energy of meso- X -rays physicists were, for the first time, able to “measure” heavy nuclei with great precision. Their radii turned out to be 30 percent smaller than the values that

appeared in the tables and textbooks of the time.

And even now this method is not inferior in accuracy to the method of measuring nuclear radii through the scattering of high-energy electrons. Moreover, the meson tool costs scientists less than a giant electron accelerator. But the comparison of these two methods loses all meaning when it comes to investigating the details of nuclear structure.

The prolonged contact of the mu-meson with nuclear matter leads to unexpected consequences. When we pull a sheet of paper quickly out of a thick stack, we do not disturb the arrangement of the other sheets; but if we pull it slowly, we can shift the entire stack. An electron, flashing through the nucleus, does not have time to affect the distribution of protons in it. A mu-meson, however, moving along an orbit located within the nucleus itself, slightly distorts the true arrangement of charges. This redistribution of nucleons, in turn, acts back upon the mu-meson, and it becomes a recorder of the new, altered properties of nuclear matter.

Theorists already distinguish certain kinds of these very small, very subtle, yet extraordinarily important effects for studying nuclear structure, which leave their mark on the meso-X-ray radiation that “probes” the nucleus.

– I wonder, does this X-ray setup for probing the nucleus resemble the one used in an ordinary X-ray

room?

- No. Physicists do not need X-ray sources. They record the X-ray photons already emitted by exotic atoms, and therefore only require the detectors. In the experimental hall of the accelerator, such a detector is even hard to notice.
- So it is a very simple setup?
- Simple in form, but complex in substance.

All the peculiarity of experiments with exotic atoms lies not in creating unusual, bulky apparatus, as is necessary in particle physics, but in achieving extremely high precision in energy measurement. The main concern of the experimenters is not to lose a single bit of information encoded in the energy and intensity of the meso-*X*-ray radiation.

For this purpose, scientists do not need large magnets or enormous tanks of Cherenkov counters, used to isolate particles moving at nearly the speed of light. The energy of the *X*-rays is relatively small. In atoms of different elements, it varies over a range of only a few to hundreds or thousands of kilo-electron-volts. The most sensitive instrument for registering quanta of such energy has proven to be the germanium semiconductor detector.

In an ordinary germanium counter, it is almost impossible to find anything that could astonish our imagination. It consists of a small cylinder with a volume of a few tens of cubic centimetres, made from chemically pure germanium. However, the manufacture of this counter requires

real craftsmanship. A tiny amount of lithium is introduced into the germanium using a very complex technology. Only after this procedure does the germanium acquire the properties necessary for the instrument.

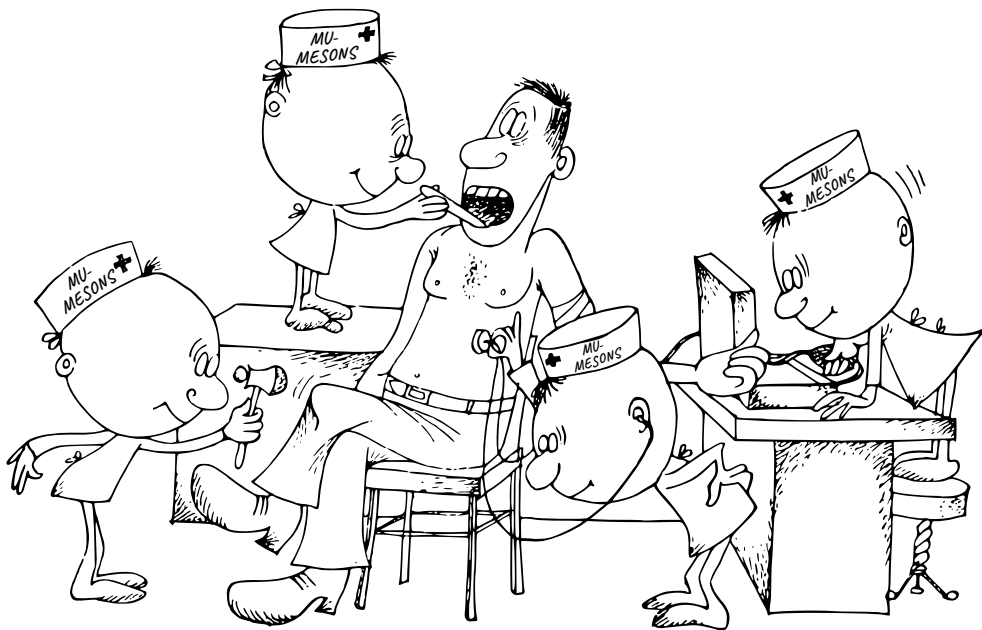
But the germanium cylinder itself, with lithium embedded in it, is still not a detector. The second part of the instrument is a very complex, sensitive, and extremely stable electronic apparatus. The entire germanium crystal is constantly within an electric field. When an ionising particle passes through the cylinder, free electrons are created along its path, knocked out of the crystal lattice, together with positively charged “holes” left behind. Under the influence of the electric field, both the electrons and the holes rapidly move toward the electrodes, which respond to their appearance with an electric signal.

The high density of the semiconductor detector material and the very low ionisation energy — ten times lower than the energy required to ionise, for example, a gas — make it simply indispensable for measuring the energy of X-ray radiation.

It must be said that scientists now use exactly the same apparatus and the same mesoatoms for other purposes as well. For example, to study changes in chemical composition in living organisms. Meso-X-ray light, with its spectral lines, is just as specific to each chemical element as ordinary X-rays.

The living and the non-living are composed of the same standard set of elements. And it is quite natural that the

results of physicists' research in the world of atoms should find application in biology and medicine. Irradiation with mu-mesons makes it possible, with the minimum possible radiation exposure to humans, to carry out rapid chemical analysis for medical diagnostics.



In many institutes around the world, accelerators are now being built, and in some already operating, which are intended not for achieving record proton acceleration energies, but for producing record-intensity beams of pi- and mu-mesons. They are called "meson factories." The

high intensity of the meson beam will help experimenters reach a higher level of precision in measuring the energy of meso-*X*-rays.

Life moves forward. And what seemed the greatest achievement yesterday already loses some of its merits today. The germanium detector, despite its excellent qualities, has practically reached the ceiling of its accuracy. A new idea has arisen — to use at accelerators a completely different method of measuring the energy of *X*-ray quanta, a method in which experimenters, as if forgetting about the energy, focus only on the precise measurement of the angle of scattering of these quanta from the plane of a crystal lattice. But what does the crystal lattice have to do with the energy of meso-*X*-ray radiation?

At first glance, none at all. But physicists studying the properties of ordinary atoms have long used crystal-diffraction gamma spectrometers for investigating atomic spectra. Their main task — the determination of the energy of electromagnetic radiation — was shifted, so to speak, onto the “shoulders” of a quartz crystal, the main component of this device. A quantum of radiation of a certain energy, falling on the plane of the crystal lattice of quartz, is reflected with maximum intensity at a definite angle. Thus, the energy of *X*-ray or gamma quanta is established with absolute precision, as if by the law of nature itself — the law governing the interaction of these quanta with the internal structure of the crystal. All that remains for the physicists is to determine the angle at which meso-*X*-ray radiation is reflected with maximum intensity. This angle depends on

the energy of the radiation and the distance between the crystal planes.

True, the instrument's designers are left with no small share of difficulties. The mechanical parts of the instrument require craftsmanship of jeweller-like precision, and the measurement of rather large angles must reach fantastic accuracy (to hundredths of an arc second!). It is also necessary to maintain a strict temperature regime – to within one hundredth of a degree. But once all these conditions are met, nuclear physicists obtain a device that measures the energy of X-ray quanta 100 times more precisely than the best semiconductor detector.

- And how sharp is the boundary separating the nucleus from the void of microcosmic space?
- The transition between nuclear matter and vacuum is rather smooth. At a distance equal to the average nuclear radius, the nucleon density is only twice lower than in the central region. The surface layer of nuclear matter makes up more than one-third of the nucleus's radius! Beyond that stretches an even more rarefied region – the nuclear stratosphere.
- Surely, in this layer of the nucleus, where there are so few particles, nothing interesting happens anymore?
- Not quite. The surface of the nucleus is just as rich in the diverse manifestations of nuclear forces as its depths.

Several pages in S. Lem's novel *Solaris* are devoted to

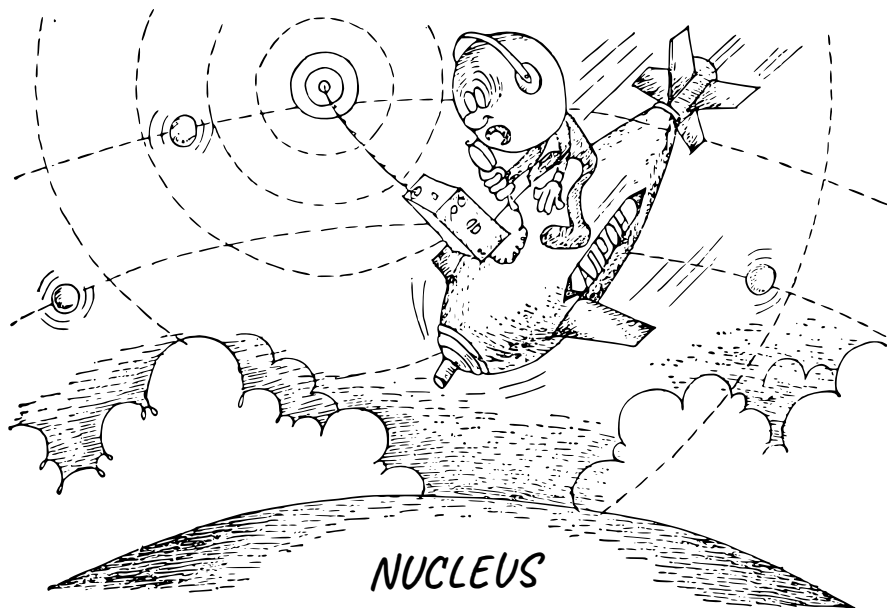
the description of fantastic waves and whirlwinds on the surface of the thinking ocean, whose inexhaustible turbulence somehow reflected its deeply hidden and incomprehensible activity, invisible to earthlings. One could write a whole poem about the surface of the ocean of nuclear matter.

Theorists suppose that in the surface, more rarefied region of the nucleus, protons and neutrons behave, so to speak, with more freedom. Here the Pauli principle, which strictly regulates their behaviour in the dense central part, acts less effectively. It is precisely at the surface that one can notice such features of nuclear matter that can never be detected in the central regions, where the density is high.

Closer to the edge of the nucleus, the number of nucleons sometimes decreases evenly. Then it is said that the nucleus has a smooth surface. But on a “bumpy” one, neutrons and protons cluster into small lumps. Theorists have certain considerations that in the nuclear “fringe” protons and neutrons briefly stick together into an ordinary alpha particle. Alpha condensations arise and then vanish again as individual nucleons, of which they are composed, moving along their individual orbits, suddenly appear at the surface of the nucleus and then dive back into its depths.

The shell model predicts the accumulation of alpha particles on the surface of the nucleus – from 100 percent in the light lithium-6 nucleus to one percent for the calcium-40 nucleus. But how things actually stand is still unclear.

The results of some experiments seem to be a very transparent hint that there are far more alpha particles on the surface than follows from the shell model. Perhaps this is so, and nothing can be done about it. As A. Einstein said: "Everything we know about reality comes from experience and ends with it."



However, even the surface layer – whose thickness is taken as the radial distance from the point where the density equals nine-tenths of its central value to the point where it falls to one-tenth – is not yet the very edge of the

nucleus.

The density of nuclear matter falls to zero at quite a large distance from the centre of the nucleus. It would seem that this remote peripheral region could not present anything unusual, since there are almost no particles left there.

But we know how much scientists have gained from the study of the “atmosphere” and “stratosphere” of the Sun. How many interesting and important phenomena were discovered precisely in this part of our star. In the nuclear stratosphere” the density of matter is 20 times lower than in the inner region, and it is here that the action of such laws may appear that could remain unnoticed when studying only the core of the atomic nucleus. Of what particles, then, does the “stratosphere” of the nucleus consist?

The surface regions of atomic nuclei are hardly amenable to theoretical analysis, and the final word remains with experiment. Yet many physicists assume that, for example, heavy atomic nuclei must have a surface layer consisting predominantly of neutrons, a kind of “neutron halo.” Incidentally, this does not contradict the data on fast electron scattering.

The halo that sometimes appears around the Sun before a sudden change of weather can be seen with the naked eye, but how can one observe the neutron halo around a nucleus?

Before experimenters learned to accelerate protons to

energies of several tens of billions of electron volts, there was no way to probe these semi-desert regions of the nucleus. Now such a possibility is provided by secondary unstable particles that are born when ultrafast protons collide with matter.

At the International Conference on High-Energy Physics and Nuclear Structure, held in 1971 in Dubna, and at the conference held in the summer of 1975 in the United States of America, one could often hear the words: “hadronic atoms.” Physicists call “hadrons” all elementary particles capable of strong interaction. This is, so to speak, their generic name. The epithet “hadronic” has been given to such exotic atoms that, in addition to protons, neutrons, and electrons, also contain hadrons: pi-mesons, K-mesons, or heavy hyperons. Hadronic atoms, as it were, are simply made for probing the most remote regions of atomic nuclei.

The mechanism for placing hadrons into orbit around the nucleus is similar to that for mu-mesons and is much simpler than launching artificial satellites of the Earth (of course, provided one has at hand a most powerful proton accelerator and a complex system for forming beams of secondary unstable particles). In this case, ordinary atoms of the substance in which negatively charged pi-mesons, K-mesons, or hyperons come to rest turn into hadronic atoms if these unstable particles become satellites of their nuclei.

Exotic atoms are fleeting, as we have already said, and

quite peculiar. The most interesting, unique information they provide is not at the moment when the hadron is captured by the nucleus – a process accompanied by catastrophe, by the explosion of the nucleus – but literally in the instant just before this event, when the relations between them are still built on half-tones.

The atomic orbits of heavy hadrons lie even closer to the nucleus than the orbits of light mu-mesons. But hadrons are unable to reach the very deepest of them. Experimenters learn of this from the energy of those *X*-ray signals that are emitted when the particles jump from one orbit to another.

The first portions of this radiation bring only electromagnetic impressions from the interaction of pi- and K-mesons or hyperons with the nucleus. The short-range nuclear forces do not yet sense in the atom a worthy partner for strong interaction. But as soon as a hadron enters the region of the “nuclear stratosphere,” the strong interaction immediately switches on, overshadowing all others. The hadron ceases to feel the atom and interacts only with the protons or neutrons on the very periphery of the nucleus. The mu-meson, however, passes through this region without noticing the nucleons at all, since its domain is weak interactions.

As the popular song goes: “one raindrop – not yet rain, one snowflake – not yet snow.” But for hadrons, the rare nucleons of the nuclear stratosphere already constitute a nucleus. And the nucleus immediately shows its character.

Its appetite for strongly interacting particles is so great that the pi-meson disappears already from the fifth or sixth orbit, whose diameter is still ten times greater than the size of the nucleus itself. And the K-meson is captured by the nucleus even earlier.

The last signal received by experimenters from a hadronic atom, the last portion of X-ray radiation, is the most valuable, because it carries the maximum amount of information about the nature of the interaction of the pi-meson, K-meson, or hyperon with the nucleus and, very importantly, about the density of protons and neutrons in the most remote, surface regions of the nucleus.

This is a unique opportunity to verify – or rather, to test in practice – many of the concepts, hypotheses, and formulas proposed by theorists to describe nuclear interactions. By fitting their mathematical constructions to the experimental material provided by exotic atoms, scientists select the most suitable values for the arbitrary parameters that enter into the formulas.

– Judging by the evidence, “foreign” strongly interacting particles cannot remain in the nucleus as long as, for example, mu-mesons. Does this mean that physicists will never obtain a detailed account of the nucleus from a hadronic eyewitness? – In general, yes. But fortunately, in the microworld there are no rules without exceptions. Nuclei have been discovered in which, together with protons and neutrons, a neu-

tral lambda-hyperon coexists quite well – a particle not without its “strangeness,” but, most importantly, capable of strong interaction with nucleons.

In 1953, Polish scientists M. Danysz and J. Pniewski studied the interaction of cosmic rays with the nuclei of photoemulsions. At that time, this was the only way to penetrate into the world of enormous energies, where each collision ended with the splitting of a nucleus and the birth of new particles.

The photoemulsion method uses only two instruments: the microscope, crafted by human hands, and a device of astonishing sensitivity, created by nature itself – the human eye.

By the tangled tracks of animals on a snowy clearing, an experienced hunter can reconstruct a struggle to the death, full of dynamism and fury. The lines traced in the emulsion by the tracks of charged particles are likewise full of movement for the physicist examining them and speak of fascinating events in the microworld.

In the picture frozen within the microscope’s field of view, a trained eye easily distinguishes the thin, continuous track of a high-energy cosmic particle that has struck directly into the heavy nucleus of the emulsion’s substance. Like a lightning bolt casually splitting the trunk of a giant tree, it shatters the nucleus, from which particles spill out.



The eye sees something resembling a star – a characteristic sign of a nuclear explosion: from a single point in the emulsion, several rays at once diverge – the tracks of charged particles.

Polish physicists, while examining photographic emulsions exposed to cosmic rays, noticed that in some stars among the other rays there appeared one quite unusual. The peculiarity of the track was not that its thickness changed with distance from the centre, but something entirely dif-

ferent. The nature of the track left no doubt that this fragment of the shattered heavy nucleus of the emulsion was itself the nucleus of some light element. What was puzzling was its subsequent behaviour.

Normally, as it rapidly gathered electrons, the charged nucleus ionised the emulsion substance less and less, and, having turned into a neutral atom, finally “swept away” its track. Yet in rare cases this nucleus also exploded, forming a small secondary star.

Physicists were greatly astonished that a light nucleus, seemingly for no reason at all, would undergo a catastrophe – and that almost within two steps of the first one. It created the impression that the fragment nucleus contained within itself a time-bomb.

The impassive witness – the photographic emulsion – objectively recorded all the details of this event. From the thickness of the tracks and their length it was possible to determine which particles, and with what energy, were emitted during the explosion of the light nucleus. The simplest assumption was that the second star was the result of the explosion of a fragment overheated” at the moment of its formation. But in that case it could not possibly have had such a long path in the emulsion and such a long lifetime – of the order of 10^{-12} seconds!

Having analysed this strange event, M. Danysz and J. Pniewski reported the discovery of the first *hypernucleus* – an unusual “hybrid” of an atomic nucleus and an unstable heavy lambda hyperon.

The neutral lambda hyperon was born at the moment of impact of the cosmic particle with the first nucleus and, unnoticed by the protons and neutrons, settled into the fragment nucleus. After 10^{-12} seconds the unstable hyperon decayed into a proton and a negatively charged pi-meson. These, together with the secondary particles knocked out of the nucleus by them, traced the rays of the second star in the emulsion.

A hypernucleus represents a unique opportunity for physicists to observe how, for quite a long time (compared to nuclear timescales), an outsider strongly interacting particle coexists with ordinary protons and neutrons. In this coexistence everything is strange, and much remains incomprehensible to this day. The uninvited nuclear lodger itself is not without oddities. Scientists even call hyperons "strange" particles. Born and disappearing in strong interactions, hyperons somehow manage to exist far longer than the allotted lawful instant of nuclear time, equal to 10^{-22} seconds.

Something else is strange. On the one hand, neutrons and protons seem not to notice the presence of the hyperon in nuclear matter, as if it were invisible to them. On the other hand, this particle settles easily into the nucleus only thanks to the fortunate circumstance that ordinary strong nuclear attractive forces act between the hyperon and the nucleons. So can one really say that the neutral lambda hyperon enters the nucleus entirely unnoticed?"

Apparently, by mutual agreement, the lodger receives

all the rights enjoyed by the permanent residents: its binding energy is approximately the same as that of other nucleons. At the same time, however, this particle deftly evades certain rules of the internal nuclear order.

A single hyperon in the nucleus does not obey the Pauli exclusion principle, just as a lone quantum bullet in armour or a single mu-meson in the nucleus does not. "This is a tremendous advantage for testing our understanding of nuclear structure," said Professor E. Pnevskii.

Scientists believe that the most promising studies are precisely those that examine nuclei under conditions different from the standard ones. Comparing such properties of hypernuclei as lifetime, possible quantum states, and others with the corresponding properties of ordinary nuclei will yield rich information both about nuclear forces and about new aspects of nuclear structure.

But the physics of hypernuclei could not develop as long as cosmic rays remained the main source of hyperons. The cases of hypernuclei being born were far too rare. Now they are produced at powerful proton accelerators in beams of negatively charged K-mesons.

In a reaction proposed in 1963 by the Soviet scientist Professor M. Podgoretskii for obtaining hypernuclei, a heavy K-meson, colliding with a target nucleus, is captured by one of its neutrons. In this process, a neutral lambda-hyperon is born, which settles into the nucleus, along with a pi-meson. This nuclear reaction has remained the main "factory" for hypernuclei to this day.

About twenty such unusual nuclei are already known. But as a result of systematic studies, undertaken by scientists in many leading laboratories, new groups of such nuclei with entirely new properties are certain to be discovered.

For now, one must speak of hypernuclear physics mainly using verbs in the future tense. It is one of the rapidly developing and most fascinating fields of microphysics, which, however, has far more potential possibilities than actual achievements.

Even so, experimenters have already discovered several hypernuclei that contain not just one neutral lambda-hyperon, but as many as two. And even that is not the limit. Theorists predict that at the new accelerators now under construction – the so-called *nuclotrons*, which accelerate atomic nuclei to high energies – it will be possible to obtain exotic nuclei with an even greater number of hyperons.

Such super-strange nuclei should be denser, since when lambda-hyperons are added their radii do not increase. The study of such unusual nuclear matter is interesting both in itself and from the standpoint of astrophysics.

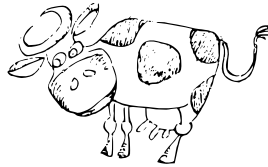
As early as 1960, Soviet astronomers V. Ambartsumian and T. Saakyan proposed a hypothesis about the existence of a special form of stellar matter – matter containing, in addition to nucleons, also hyperons.

Perhaps a time will come when hyperon physics will allow scientists to catch “stars from the sky” and study them

in the laboratory. Exotic nuclei containing several hyperons could serve as a microscopic, short-lived “sample” of stellar matter.



NUCLEI IN THE UNIVERSE AND IN OUR HOMES



4 Nuclei In The Universe And In Our Homes

– So, it turns out that nuclear matter can be stuffed with different particles? But how does rationalisation work in the microworld? If identical nuclear forces act between protons and neutrons, does it not follow that there could exist nuclei made, for example, entirely of neutrons? – Nature is a brilliant rationaliser. And when the need arises, it indeed creates neutron matter.

On the sixth of August 1967, a young assistant to Professor E. Hewish, observing the constellation of Vulpecula with a radio telescope, recorded an unusual signal: on the tape emerging from the high-speed recorder, clearly visible were remarkably regular, time-repeating bursts. This momentous event took place at the Cavendish Laboratory of Cambridge University; the very laboratory where

J.J. Thomson first proved the divisibility of the atom by discovering the elementary particle – the electron; a laboratory closely associated with the name of E. Rutherford.”



No one before had ever received such strange signals from space. They were eerily reminiscent of the repeatedly described alien transmissions in science-fiction literature. One would think that the astronomers should have immediately informed the world of their discovery and attempted to decode the information about distant worlds hidden in the mysterious impulses. But scientists

are peculiar people. And the most conscientious among them seem doubly peculiar.

The English astronomers, above all, began to doubt the results and devised the most uninteresting, the dullest explanations for the appearance of these unusual impulses.

Before contemplating extraterrestrial civilizations, the discoverers preferred first to test the hypothesis that the signals were interference originating from our own terrestrial civilisation, such as emissions from radar stations, television transmitters, or satellite communication systems. Thorough investigations proved fruitless. The signals, which varied in intensity, could not be identified with any known Earth-based transmitter. Moreover, shortly thereafter, the same observatory detected three more analogous pulsating sources of radio emission.

Some time later, the scientists became fully convinced that the sources of these strange signals were located far from Earth. But why had no one, aside from the English astronomers, received such transmissions?

Not so long ago, scientists realised that space is multilingual, that it communicates with us through photons of visible light and streams of invisible but all-penetrating neutrinos, and that it conveys some of its messages in the language of gamma quanta, cosmic rays, and radio waves in various ranges. The staff of the Cavendish Laboratory were precisely studying shortwave cosmic radio emission with variable intensity. In the summer of 1967, they first obtained the opportunity to listen to the Galaxy in the range

of relatively long radio waves.

Signals unlike anything else were registered almost immediately, as soon as the special radio telescope, which no other observatory in the world possessed, began to operate. The device, unprepossessing in appearance, had been constructed by the institute's staff to the very latest technical standards. And the Cambridge scientists turned out to be the only people to whom space could communicate something entirely new.

However, these results did not so much delight the astronomers as alarm them; they were struck by an incredibly high frequency of pulsations, quite uncharacteristic of cosmic objects – up to several dozen cycles per second – and by the regularity of repetition, so precise that even the most accurate electronic clocks could be checked against it.

The English astronomers decided to keep the obtained data in strict secrecy until the nature of the signals was clarified. “The first thing that came to our minds was that we were dealing with artificial sources – signals from ‘little green men,’” said Professor A. Hewish in an interview. The scientists were seriously disturbed by the thought that perhaps somewhere nearby a powerful civilisation had arisen, whose intentions were unknown to anyone.

The only natural sources of the discovered radio emission could be extremely tiny, on an astronomical scale, superdense bodies. And since modern science did not rule out this possibility, Professor A. Hewish soon suggested

that the pulsating emission probably belonged to small stars – “white peas,” as he called them. When a journalist asked: And what is better, Professor? (‘Little green men’ or ‘peas’? – Author), A. Hewish firmly replied: “Peas, my dear, peas. Personally, vegetables have never done me any harm.”

In February 1968, that is, six months after the first registration of cosmic signals, an article appeared in the English journal *Nature*, from which the world first learned about the discovery of unusual, pulsating cosmic objects – pulsars.

Among physicists, astronomers, and astrophysicists, discussions flared up with unprecedented intensity on the question of what pulsars actually were. Some scientists, apparently not without the influence of science fiction (a rare example of the direct influence of art on science), continued seriously to insist on the artificial origin of the recorded radio pulses. Such an assumption freed theorists from the need to think and to search for a simpler explanation. “I think that the idea of extraterrestrial civilisations in this case deserves the most serious attention only in connection with the onset of the summer holiday season,” began academician V. Ginzburg in his short address at the monthly scientific session of the USSR Academy of Sciences, held in May 1968.

While the experiment had not yet set sufficiently strict limits for theoretical reasoning, the debates were especially heated. “I am myself a theorist,” said V. Ginzburg,

“and I know that one can talk about theory for a long time, especially if nothing definite is known about the object.”

But as experimental data accumulated on the sources of radio emission of variable intensity, the chances of one hypothesis grew so much that pulsars were finally and unconditionally recognised as rapidly rotating, small but superdense neutron stars. Like the light beam of a rotating lighthouse, the radio beam from an active region on the surface of a neutron star periodically became available for observation on Earth.

From the very moment the elementary particle – the neutron – was discovered, the idea also arose of the existence of neutron stars, tiny superdense remnants of former cosmic giants. This hypothesis touched upon both the problem of stellar evolution and the problem of the evolution of nuclear matter.

In the microworld, the fate of atomic nuclei is decided mainly by nuclear and electromagnetic forces. And only rarely does the weak interaction play a noticeable role ... But what governs the matter of a neutron star, which, with a radius of 10 to 20 kilometres, has a mass comparable to that of the Sun?

Over massive cosmic bodies there constantly hangs the threat of gravitational compression. They manage to preserve themselves in the state of ordinary matter only so long as energy is continuously released in their depths, which from within compensates the force of gravity. But when this energy is exhausted and the star can no longer

struggle against gravity, its matter turns into a dense neutron “dough”. And then the star becomes as monstrously dense as an atomic nucleus.

The heaviest of the known nuclei contains several hundred particles. If from such a “snowball” one were to roll a gigantic nuclear lump containing no fewer than 10^{56} nucleons, one would obtain a *neutron star*.

The mysterious cosmic body that so frightened scientists with its signals is nothing more than a gigantic atomic nucleus – a nucleus in which the gravitational energy per nucleon is equal in magnitude to the nuclear energy.

Under these conditions (conditions of monstrous pressure) protons are converted into neutrons by the forced attachment of electrons to them. And neutron matter, with a small admixture of protons and electrons, governed by gravitational and nuclear forces, begins a new life as a *pulsar*.

- Probably, if one set out to obtain a drop of neutron matter, it would be enough to remove protons from the nucleus, and it would become super-strong, since only neutrons would remain in it, which would not repel one another, as they have no electric charges.
- Yes, repulsion would disappear, but with it would also vanish the conditions necessary for the existence of a bound system of nucleons. Without protons, it turns out, neutrons cannot form not only a super-

strong nucleus, but not even an ordinary one.

Let us try to imagine such an atomic nucleus from which all protons have been carefully removed. How would the remaining neutrons in the nucleus react to such an operation? It would seem that they would immediately fill all the vacated places in the deepest shells, and we would obtain the desired neutron matter with ordinary nuclear density.

But the Pauli principle relentlessly ensures that neutrons do not occupy the quantum states forbidden to them in the proton shells. And a half-empty nucleus without protons becomes less stable.

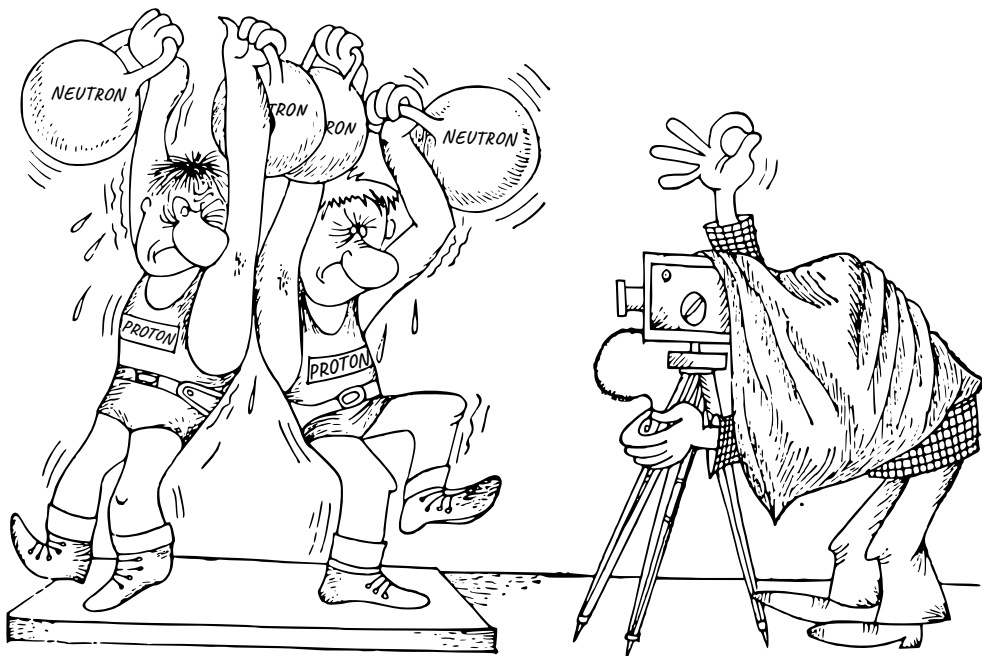
Such neutron matter is nothing like pulsar matter: it is loose, and the distance between the particles in it is greater than average nuclear distances. It is a genuine neutron gas, in which the nuclear forces of attraction may not be able to cope even with the kinetic energy of the neutrons flying apart.

Under the unusual conditions of neutron stars, neutrons are forced into proton positions by super-powerful gravitational pressure, while in a terrestrial nuclear drop the necessary viscosity, it seems, can be provided only by the protons themselves.

And yet the question of the existence of neutron matter remains open. Theorists do not deny that its stability may increase with the number of particles in the drop. There-

fore, experimentalists, having failed to detect a bound system of two neutrons, continue persistent searches for heavier neutron drops.

An athlete holds a record weight for only a few seconds — and the panel of judges records a sporting victory. Let a bound system of several neutrons fall apart after an instant. That is enough for instruments to register a neutron nucleus and for nuclear physicists to claim a new achievement.



Can a neutron drop exist or not? — this question theorists answer sometimes in the affirmative, sometimes in the negative. A. Migdal, based on his theory of the pion condensate, believes, for example, that neutron matter can and must exist, since the condensate helps strengthen the binding between nucleons. Only experiment will put an end to the oscillations.

Neutron matter can also be attempted by adding more and more neutrons to a light nucleus. Soviet scientists Ya. Zeldovich and V. Goldansky, in 1960, on theoretical grounds predicted that it would be possible to create an entirely unusual, neutron-saturated isotope of the chemical element helium. The nucleus of the widely distributed stable helium-4 in nature contains two neutrons and two protons; this is the well-known alpha particle. The scientists claimed that around the two protons of the alpha particle not two, but as many as six neutrons could be bound!

The hypothesis was so enticing that experimentalists, despite its seeming unreality, decided to try to obtain the phenomenon imagined by the theorists. First they checked whether an alpha particle could attach one more neutron. It turned out that this was beyond its capacity. From two protons and three neutrons, a bound system did not arise. They then attempted to obtain the helium-6 nucleus. The attempt was successful. Among the products of the spontaneous fission of californium-252, American researchers registered about a hundred such nuclei. Two protons held four neutrons for some time.

The record weight was lifted, but it was still not the maximum possible. Only a few years later did the first reports of a new triumph begin to appear. In the interaction of high-energy protons with carbon nuclei, in the fusion reaction of fast alpha particles with a magnesium-26 nucleus, and in the absorption of high-energy gamma quanta by a boron-11 nucleus, there sometimes arose the fantastic helium-8 nuclei, in which the protons were outnumbered threefold by neutrons.

Finally, a group of physicists at the Laboratory of Nuclear Problems of JINR, led by Doctor of Physical and Mathematical Sciences V. Sidorov, obtained the most indisputable evidence of the birth of a nuclear, almost neutron droplet, consisting of two protons and six neutrons. A nuclear emulsion forever preserved the autograph of this wonder-isotope, produced in the reaction of a slow pi-meson being absorbed by a light carbon nucleus.

Continuing their research on the interaction of pi-mesons with atomic nuclei, the same group of physicists discovered a new nuclear reaction — a reaction that paved the way to the synthesis of isotopes with an excess of neutrons, and perhaps even purely neutron nuclei.

In emulsions irradiated with a beam of negatively charged pi-mesons at the synchrocyclotron, the experimenters were looking for cases where one meson entered a nucleus and two emerged — that is, stars with three rays. Yet, from time to time, strange stars with only one outgoing ray appeared in the microscope's field of view. Moreover, the

emerging meson always had a positive charge. Each time they saw such a star, the researchers could not help but ask themselves the same question: "Where is the second, negatively charged pi-meson, the one that created the star and normally also emerges from the nucleus?"

One could have ignored these stars with a missing ray. After all, who knew what could have happened to the negative pi-meson: it could have been absorbed by the nucleus, turning into a neutron that left no trace in the emulsion. These reactions were well known and had a fairly high probability. Yet one persistent thought troubled the scientists: "What if the very same pi-meson that caused the nuclear reaction actually emerged from the nucleus, having somehow changed its negative charge to positive inside?"

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But how many changes were provoked in the nucleus by the pi-meson that lingered there for just a moment!

The nucleus suddenly lost two protons — two units of electric charge, and therefore two units in the atomic number of the element. This new isotope, enriched with neutrons, now had to take a place two cells closer to the beginning of the periodic table.

Equally original is the behaviour of pi-mesons with a positive electric charge in relation to atomic nuclei. Passing through a nucleus, such a positively charged pi-meson reacts with two neutrons. It turns them into protons and itself leaves the nucleus as a negatively charged particle. The remaining nucleus, without losing a single nucleon, becomes a new isotope of a chemical element, located two cells further in Mendeleev's periodic system.

This is a true nuclear illusion — a feat of art that even the most famous magician would surely envy.

The modest-looking stars in the emulsion, noticed by the keen-eyed researchers, turned out to be echoes of profound transformations of atomic nuclei in the reaction of double charge exchange.

The discovery made by the scientists of JINR opened the possibility of conducting experiments aimed at producing unusual nuclei with a planned number of protons and neutrons, and it helps to establish in what combinations neutrons and protons can create bound systems.

At present, in many laboratories, experimenters are attempting in various nuclear reactions to detect the birth of the tetraneutron — a bound system of four neutrons.

In the Laboratory of Nuclear Problems at JINR, an original experiment was carried out to search for the tetraneutron, which could arise in the reaction of double charge exchange of a pi-meson on a lead-208 nucleus.

The physicists did not expect that the hypothetical neutron droplets would seep out of the thick lead target. The “thirsty” lead nuclei could instantly absorb these four neutrons and turn into heavier nuclei of the isotope lead-212. After a rapid radioactive decay, these nuclei could transform into bismuth nuclei, with a lifetime of about an hour.

A difficult task now faced the physicists and chemists: they had to extract from a kilogram block of lead a mere handful of atoms of radioactive bismuth. With great excitement, the experimenters registered several alpha particles that belonged to the decaying atoms of bismuth. American scientists repeated this experiment and obtained a similar result.

So does this mean that physicists have proven the existence of the tetraneutron?

No, the scientists did not hasten to draw that conclusion. On the basis of such a small number of detected particles it was still impossible to make a radical claim. The alpha particles could also have belonged to bismuth nuclei that had accidentally entered the apparatus.

Perhaps the tetraneutron cannot exist at all? In that case, it is worth searching for heavier neutron nuclei. By means of the double charge-exchange reaction, scientists are attempting to obtain a “fragment” of neutron matter consisting of six neutrons.

The Dubna experimenters traced, in an emulsion irradiated with pi-mesons, the unusual fate of two nitrogen nuclei. Out of the 14 nucleons of the nitrogen nucleus, after its encounter with pi-mesons, 8 regrouped into a boron nucleus. Under the microscope, the characteristic track of this nucleus was clearly visible. And the remaining six (all six of them neutrons!) rushed off in search of new nuclear adventures. Might they form, if only for a brief moment, a six-neutron nucleus?

As soon as powerful accelerators – true “meson factories” – are available to the scientists, the problem of neutron droplets may at last be solved.

- But if neutrons need protons so much, then surely physicists know exactly how many of them are required for the nuclei of different elements?
- No. The theory of nuclear matter cannot yet give a

definite answer to that question.

- And what does experiment say?
- Experimenters are persistently breaking through to the boundaries of nuclear stability and are already placing the first boundary markers.

Until physicists began to interfere with the affairs of nature, it contained mostly stable nuclei and a small number of long-lived radioactive isotopes.

If one draws rectangular coordinates on a sheet of paper, placing the number of neutrons on the X -axis and the number of protons on the Y -axis, then all the stable nuclei that make up our world will obediently lie almost on a single line, which physicists call the line of stability. At first it runs at an angle of 45 degrees to the neutron axis, and then it increasingly bends in its direction.

In light nuclei there are equal numbers of neutrons and protons. But the greater the charge of the nucleus, the harder it becomes for the nuclear forces of attraction to overcome the increasing electrostatic repulsion of the protons.

Nature resolved this difficulty by endowing heavy nuclei with matter almost twice diluted with neutrons. With such powerful support, the forces of attraction secured the stability of nuclear matter even for very heavy chemical elements.

Thus, the line of stability is the region of the most stable

nucleon collectives, in which the nuclear forces of attraction have gained a complete victory over the repulsive forces of protons.



It is impossible to determine the safety margin of any structure without creating deliberately unfavourable conditions for it. Biologists deliberately introduced chimpanzees into our Pskov forests in order to observe, under unusual conditions, how their capacity to adapt to a new environment would manifest itself. At one conference someone

wittily remarked that to study the properties of nuclear matter only through stable nuclei is the same as to study the geography of the United States through the Grand Canyon.

After the discovery of artificial radioactivity, scientists eagerly set about expanding the range of isotopes. They managed to obtain quite a number of different modifications of existing chemical elements with a slightly different ratio of protons to neutrons. These artificially created nuclei occupy on the chart a certain area around the line of stability. Let us call it the “continent of stability.”

Of course, the new acquisitions of physicists did not live long, and after radioactive decay they returned once again to their familiar places near the line of stability. But the very fact of the appearance of unusual bound systems provided abundant food for thought. It goes without saying how interesting it was to find out to what extent atomic nuclei, even if short-lived, could be oversaturated with protons and neutrons. In a word, it was necessary to find the boundaries of the existence of nuclear matter. To see what was happening there, at the edge of the nuclear Ocean?

A guidebook for experimenters, compiled by theoreticians, somewhat resembles the travel manuals that existed, for example, among the ancient Egyptians. Which modern traveller would dare to seek a land that lies there, beyond the eastern desert, beyond the azure waters, in the immeasurable distance?

“There” – declares the guidebook for nuclear physicists

– “on both sides of the line of stability, at the very edge of the continent, where the forces of attraction in nuclei with a great excess of protons or neutrons are no longer able to cope with their task, there lie steep cliffs, washed by the waves of the sea of instability...”

More precisely specifying the coordinates of the boundaries of the continent of stability – that is, the ratios (different for different elements) between the number of protons and neutrons at which a nucleus decays the very moment it arises – is beyond the capacity of modern theory. The exact location of the cliffs will have to be determined by the experimenters themselves.

Within its own competence, theory promised thrilling encounters with at least six thousand new radioactive isotopes. Of these, acquaintance has already been made with two thousand. The energetic search for the remainder is still underway.

The expansion of the collection of isotopes, which differ greatly from those already known, is not a hobby of experimenters. These curious varieties of nuclei of ordinary chemical elements provide scientists with information previously inaccessible and help them to better understand the structure of the nuclei that populate the line of stability.

Experiments with pi-mesons enabled physicists to discover, far away from the line of stability, the remarkable helium-8 nucleus with six excess neutrons. By means of the double charge-exchange reaction of pi-mesons, re-

searchers, like opening tins with a can-opener, prise open nuclei containing nucleons and, according to a predetermined programme, alter the composition of nuclear matter. But this delicate operation does not allow one to reach the very boundaries of the region of stability.

The most exotic assortment of nucleons can be obtained if one strikes one nucleus against another with great force. Such experiments are carried out on special installations — heavy-ion accelerators. In these machines not individual protons with a single unit of electric charge are accelerated, but whole atomic nuclei, up to the heaviest ones.

Every fourth accelerator in the world now operates in the heavy-ion mode.

The most powerful heavy-ion accelerator is at the Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research in Dubna. There, using ions accelerated to energies that allow them to overcome the electrostatic barrier surrounding the target nuclei, experimenters attempt to break through to the boundaries of stability of nuclear matter.

When the contents of two nuclear “cans” merge, an overheated heavy composite nucleus is formed. It is impossible to predict in advance what the final combination of protons and neutrons will be after the reaction: the outcome depends on how the nucleus rids itself of excess energy. If the nucleon system relaxes to a normal state by evaporating neutrons, physicists obtain a new nucleus

with an excess of protons.

But sometimes the colliding nuclei cling together and for a while resemble a dumbbell, rotating as a single whole. As it spins, the dumbbell deforms and eventually breaks apart: Coulomb electrostatic repulsion and centrifugal forces overcome nuclear attraction.

For experimenters, this is all the better, because in the rupture of such a complex system two or three dozen nucleons of one nucleus are transferred to the other, producing an extraordinary mutant of a familiar chemical element.

By irradiating thorium-232 targets with oxygen-18 and neon-22 nuclei, scientists at the Joint Institute for Nuclear Research created more than ten new heavy isotopes. Among them were a carbon nucleus with twelve additional neutrons and oxygen nuclei containing fourteen, fifteen, and even sixteen more neutrons than the stable nucleus of the same element.

The successes of experimenters crafting nuclear matter of such extraordinary structure compel astonishment at the truly boundless power of nuclear forces. At the International Conference in Montreal in 1969, the distinguished American physicist Professor H. Gove remarked in his keynote address that "the physics of nuclear structure will remain an exciting field of research for many years to come."

Over the past quarter of a century, particle physicists

have discovered an immense world of elementary particles. Most of these microscopic entities, born in high-energy accelerators, barely had time to announce their existence – tracing a fine line in photoemulsions, leaving a misty track of bubbles in a hydrogen chamber, or triggering counter systems. Yet these unstable quanta of matter have vastly expanded our understanding of the structure of the universe. New laws of nature have been revealed, some seemingly inviolable principles of quantum mechanics have shown exceptions, and we have learned of the charge-conjugated world of antiparticles.

Nuclear physicists have discovered a vast world of ghostly isotopes on both sides of the line of stability – a world incomparably richer than that of the chemical elements. It has been found that the nuclei of the same element, one with an excess of neutrons and another with an excess of protons, differ as much from each other as a dachshund differs from a Moscow watchdog. The collective of nuclear nucleons responds sensitively to changes in the proportion between its two types of members. The structure of nuclear matter changes accordingly, and an excess of neutrons even causes the nucleus to swell, expanding from the overfilling of its outer neutron shells.

Experimental results on the creation and study of the properties of this new nuclear world compel scientists to view nuclear forces in a new light. Here, at the edges of the continent of stability, nuclear forces, far from weakening, reveal themselves with remarkable vigour. In regions near the limits of nuclear matter stability, physicists have discov-

ered new doubly magic nuclei, new domains of deformed nuclei, and new types of radioactive decay.

A short-lived bound system of nucleons deficient in neutrons behaves in a way quite unusual for nuclear matter – it becomes an emitter of delayed protons. And a nuclear “drop” with a large excess of neutrons, according to theorists, may act in an even more unprecedented manner – by emitting pairs of neutrons.

– And according to the guide, how does the line of stability end in the region of the heaviest nuclei? – The guide predicted a steep cliff there as well – marking the final and absolute triumph of the forces of repulsion over the forces of attraction.

Forty years ago, Mendeleev’s periodic table ended with the ninety-second chemical element – uranium. No heavier elements were found in nature. The line of stability also came to an abrupt end at the uranium nucleus.

The breakthrough beyond the uranium frontier was achieved by the Italian scientist Enrico Fermi. By bombarding uranium nuclei with neutrons slowed to thermal speeds (that is, to the velocity corresponding to the thermal motion of molecules at room temperature), Fermi obtained the first transuranic, ninety-third, element – *neptunium*.

One after another, seven new types of nuclei were torn by physicists from nonexistence; seven new chemical elements became available for chemists to study. Just as

the area of the Netherlands steadily grows through land reclaimed from the sea, so the periodic table lengthens through the artificial creation of new nuclei.

The work on synthesising transuranic elements, up to the hundredth – named *fermium* in honour of Enrico Fermi – was not especially difficult for physicists. The method in principle did not differ from the one used by Fermi himself. Experimenters placed heavy nuclei in a powerful stream of neutrons, for instance in a nuclear reactor, and waited for time and beta decay (the decay of a nuclear neutron into a proton, an electron, and a neutrino) to do their work.

Everything went smoothly. The heavy nuclei obediently swallowed neutrons, and after beta decay, reliably turned into nuclei of elements with an atomic number one unit higher.

However, after the hundredth element, fermium, this process consistently failed. The nucleus of fermium-258 no longer yielded a beta-radioactive isotope of fermium-259. It underwent spontaneous fission before it could perform the role expected of it.

The calm period was over. Physicists realised that beta decay was no longer their ally. To move further into the transfermium region, they had to find a new guide. It turned out to be the reaction of a heavy nucleus capturing accelerated alpha particles or deuterium nuclei – the isotope of hydrogen.

An alpha particle delivered two new protons to the nucleus at once, so the target need not be fermium but could be made from the longer-lived ninety-ninth element, einsteinium-253. But where were such heavy nuclei for a target to be obtained? No chemist in the world could fulfil an order to manufacture such a target; the einsteinium nuclei first had to be “grown” in a nuclear reactor.

By 1955 about 5×10^{-7} microgram of the ninety-ninth element had been accumulated, and this was used for the synthesis of the hundred-and-first element. And so, in the reaction einsteinium nucleus + alpha particle, the first seventeen atoms of the new hundred-and-first element were produced, and the element was named mendelevium in honour of the outstanding Russian chemist D. Mendelev.

But with such an ephemeral einsteinium target the experimenters could obtain only one atom of mendelevium per hour. How long, then, would one have to wait for a sufficient number of nuclei to make a target of the hundred-and-first element?

It became clear to the scientists that even with light charged particles one could not advance very far.

They obtained a reliable guide into the transfermium region only after the creation of heavy-ion accelerators. And the nightmarish problem of growing nuclei for targets ceased to exist. The distant transfermium region could be reached by bombarding targets made of lighter substances with complex nuclei.

But the route chosen by the physicists – a path no one had yet trodden, leading into a region lashed by the waves of the sea of instability – proved arduous. The targets contained a fairly large quantity of material, the accelerator provided intense ion beams, and yet the nuclei of new transfermium elements again appeared, as the saying goes, by the teaspoonful. Several dozen atoms of the 102nd element per hour, and only one atom of the 105th element in tens of hours, could be produced on a heavy-ion accelerator working at full power.

The efforts expended were almost wasted. The fission reaction, as if mocking the hopes of the physicists, repeatedly cleaved the painstakingly produced heavy compound nuclei in two. Only a small fraction managed to avoid this fate, cool by evaporating neutrons, and survive as heavier nuclei.

But a route is not considered traversed unless there are marks at the checkpoints. For the physicists threading their way through the transfermium region, a checkpoint is the discovery of the next, heavier nucleus. The mark that a stage has truly been passed is the definite identification of a new element – necessary for assigning it an atomic number in the periodic table.

It was necessary to carry out extremely delicate work to determine the nuclear charge, the mass, the lifetime, and the mode of radioactive decay when producing atoms that decay faster than they can be gathered together.

None of this would have been possible without the

law of conservation of energy and momentum. A heavy nucleus, on capturing the accelerated ion, simultaneously acquires its momentum and, like Baron Münchhausen on a cannon, is expelled from the target. All that remains is to catch these product nuclei and convey them from the irradiation zone to the area for analysis of their chemical and physical properties.



In some experiments, this task was accomplished by a stream of helium – a “helium wind”. The target was placed

in a chamber filled with helium at a pressure of one atmosphere. A half-millimetre hole connected this chamber to another, from which the air had been previously evacuated. The gas from the first chamber rushed toward the opening, carrying with it the heavy nuclei knocked out from the target. At a distance of one centimetre from the hole, the helium jet struck a specially positioned collector, on which the new nuclei settled. The collector – for example, an aluminium wheel rim – was moved so as to bring the collected nuclei directly to the detectors that recorded the radioactive emissions from these unstable atoms.

The very short lifetimes of the transfermium elements made it impossible to carry out the necessary chemical identification of the obtained atoms using traditional methods. A kind of record was considered to be the chemical identification of the 101st element, mendelevium, based on the decay of 17 of its atoms, with a half-life of one and a half hours.

It seemed that radiochemists were at a loss – what could they possibly do when it came time to determine the chemical properties of the 104th element, kurchatovium, whose number of atoms is reduced by half in a fraction of a second?

And yet, the group of radiochemists at the Joint Institute for Nuclear Research (JINR) Laboratory of Nuclear Reactions, led by the Czechoslovak scientist I. Zvára, managed to solve this problem. They created a continuous-operation chemical conveyor which, through reactions in a gaseous

medium, made it possible to detect and study the chemical behaviour of only twelve atoms of kurchatovium in the very first measurements.

The discovery of the next element, the 105th, at the heavy ion accelerator in Dubna at the beginning of 1970 required great effort from the physicists. This element was obtained by irradiating an americium target with accelerated neon nuclei. The 95 protons of the americium nucleus merged with the 10 protons of neon to form the nucleus of a new element with 105 protons.

The requirements for the purity of the target in this experiment were so stringent that they initially caused the laboratory chemists a painful sense of unease. The americium had to be completely free of lead impurities, which could have produced an undesirable background during the irradiation of the target.

The “tragedy” lay in the fact that the entire laboratory – like any other where work with accelerators was conducted – was literally filled with lead. A complex operation was ahead. Without wasting any time, they drew up a map showing the distribution of lead throughout all the laboratory rooms. Each room, including even the director’s office, was cleaned with vacuum cleaners, and the collected dust was specially examined for the presence of lead.

From the rooms where work with the target was carried out, all books, journals, brochures – in short, all printed materials – were removed. Not even a fresh newspaper could be looked at during the lunch break. This total war against

lead eventually led the chemists to produce a target that approached semiconductor purity. The lead content per gram of americium did not exceed a few ten-thousandths of a microgram.

Those responsible for creating a mechanism capable of transferring the collectors containing atoms of the 105th element to the counters in a very short time also had plenty to worry about. One proposal even suggested a device resembling a machine gun: the nuclear collectors would be shaped like bullets, with the nuclei carried by the gas from the target chamber gathering on them, and then these bullets would be shot towards the detectors. However, the experimenters settled on a more “peaceful” – pneumatic – device.

Thus, by 1970, the scientists in Dubna had created new elements that filled the cells from 102 to 105 in the periodic table. Similar experiments were being conducted at the Lawrence Radiation Laboratory in the United States.

Then, in 1974–1975, at the Laboratory of Nuclear Reactions, when a lead target was bombarded with chromium ions, an isotope of the 106th element was obtained, and in the reaction of manganese ions with bismuth nuclei – the heaviest element of Mendeleev’s table so far, with atomic number 107. Both these isotopes exist only for a few milliseconds.

- ‘Does that mean it is already the limit? The steep edge of the continent of stability?’
- ‘Both yes and no. The descent from the plateau turned out to be not quite as theorists had imagined, and they had to hurriedly issue a new guidebook, the final section of which was, in fact, a navigational chart.’
- ‘So, is a voyage across the sea of instability being proposed?’ – ‘The theorists believe that daring sailors have every right to hope for the discovery of islands of stability. Who knows, perhaps the physicists too will one day find their own Easter Island.’

Among the transuranium elements, there were some whose lifetimes stretched into tens of thousands of years. But in the realm of superheavy nuclei, an epidemic of instability raged in full accordance with the predictions of the liquid drop model. It seemed that controlling such vast assemblies of nucleons was indeed beyond the strength of nuclear forces.

According to theory, the chemical elements following the 105th were expected to have such short lifetimes against spontaneous fission that, with the existing level of experimental technology, their production would be impossible. The fission catastrophe, as physicists dubbed this fatal barrier, seemed about to put an end to their quest. But, as P. Kapitsa once said, a good experiment is one that does not agree with theory.

Experiments conducted on heavy-ion accelerators for

the synthesis of the 105th, 106th, and 107th elements showed that the fission catastrophe had not occurred. The isotope of the 105th element discovered at the Laboratory of Nuclear Reactions had a lifetime of two seconds, while American scientists reported obtaining an isotope of the 105th element with 262 nucleons that lasted twenty times longer. The scientists in Dubna are now attempting to produce longer-lived nuclei of the 106th element.

Not far from the steeply descending continent of stability, physicists unexpectedly found a shallow in the sea. What, then, was slowing down the onset of the fission catastrophe? The cause could only be a sufficiently distinct shell structure in heavy nuclei – the very structure once thought to be the privilege of light and medium-mass nuclei. Otherwise, it would be impossible to explain why the nuclei of fermium-256 undergo fission after 2.7 hours, whereas the isotope fermium-257, with just one additional nucleon, does so only after one hundred years.

The arrangement of neutron shells affects nuclear stability so strongly that even the addition of a single neutron to 250 nucleons does not go unnoticed. The coastal “shelf” discovered by experimenters can therefore be regarded as a manifestation of shell effects in the nuclei of superheavy elements.

This encouraging discovery inspired new hope. Theoreticians looked more boldly towards the presumed limit of the periodic table and, consulting the equations derived from the shell model, charted a course to the islands of

stability.

One of these islands corresponds to the heaviest atomic nucleus with a new magic number of protons – 114 – and a new magic number of neutrons – 184. The other, even heavier, nucleus has the magic numbers 126 protons and 184 neutrons.

These two distant and mysterious islands of superheavy elements once again robbed physicists of their peace. They began restlessly pacing the transfermium shore, inventing every possible means to bridge the gap that separates them from the longed-for islands.

The Director of the Laboratory of Nuclear Reactions at JINR, Academician G. Flerov, said that “the discovery of the islands of stability will be as important for nuclear physics as the discovery of America was in its time for mankind.”

But how could one achieve this goal – to prove that superheavy nuclei exist?

At present, accelerators of heavy ions are not yet capable of directly synthesising nuclei containing 114 or 126 protons. Therefore, scientists decided to check whether there might be a narrow isthmus connecting the mainland to the nearest island of stability.

From uranium to the nearest goal lie twenty-two chemical elements – twenty-two steps along the heaviest of routes. Fifteen steps have already been taken, each one cautiously, as if testing the ground underfoot. At any moment, the coastal shelf could give way to the bottomless

depths of the sea of instability. Yet the bold explorers continue their journey and are already preparing experiments to synthesise still heavier nuclei.

Another group of researchers was inspired by theoretical predictions suggesting that the lifetimes of elements adjoining the islands of stability may vary across an enormous range – from hundreds of millions of years to microseconds. In truth, the theoreticians could not say anything definite on this matter.

As soon as the idea arose that the hypothetical islanders might possess extraordinary longevity, experimentalists immediately set sail – quite literally – into the Pacific Ocean in search of nuclei of superheavy elements.

Cosmic rays from sources located somewhere near the centre of our Galaxy reach our modest Solar System after roughly 10^5 – 10^6 years. If these rays contain long-lived nuclei of superheavy elements, it might be possible to find such nuclei on the Earth's surface. The overall number of heavy-element atoms falling upon Earth is extremely small, so it makes sense to examine only those objects capable of accumulating them over vast stretches of time.

In the seas and oceans that cover most of the Earth's surface, heavy elements such as manganese and iron gradually precipitate onto remnants of organic origin scattered across the seabed – such as shark teeth. A layer just one millimetre thick takes about one hundred thousand years to form. Thus, in such ferromanganese concretions – dense, dark-coloured spheres about five centimetres in diameter

– atoms of elements from the island of stability, having arrived from space, might accumulate.

Superheavy elements may also be present in natural minerals and ores, if the nuclei of these superheavy atoms – so far existing only in the imagination of theoreticians – truly possess lifetimes comparable to the age of the Earth itself.

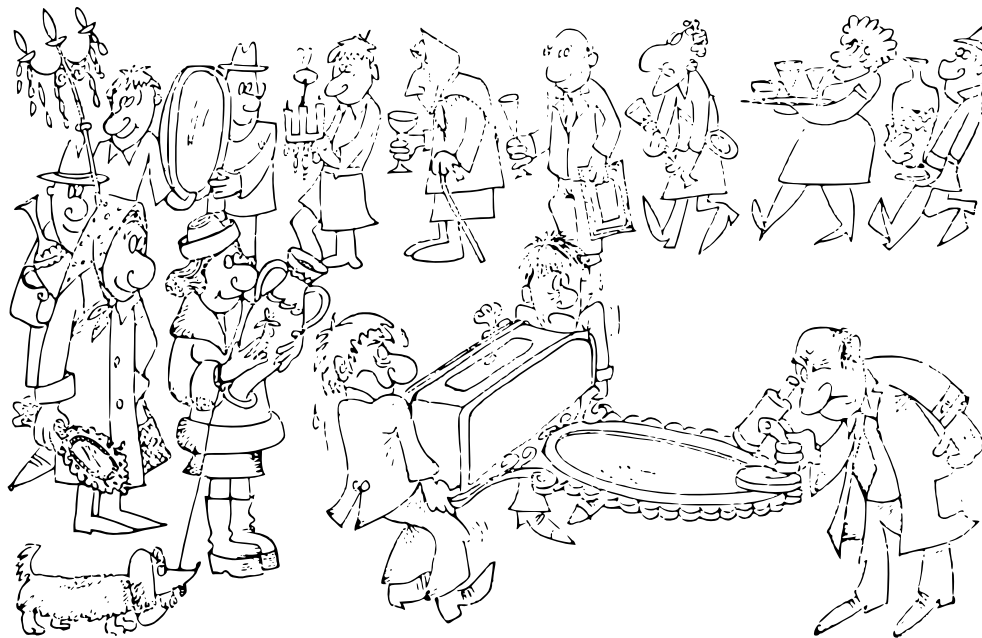
Scientists believe that element 114 should, in its chemical behaviour, resemble lead. Therefore, researchers at the Laboratory of Nuclear Reactions are meticulously analysing samples of lead ores sent from various parts of the world.

In the laboratory rooms, cupboards have appeared filled with antique mirrors and goblets of glass – objects one might expect to find in an antique shop rather than among scientific instruments. The reason for this unusual interest in relics of the past is simple: together with the lead used by medieval glassmakers, a similar but far heavier element from the island of stability might also have found its way into the glass.

Over the centuries since the glass was made, the superheavy nuclei could have decayed, leaving behind microscopic regions of structural damage. Through chemical treatment, these traces of decay become visible as tracks that can be observed under an ordinary microscope.

Superheavy elements have also been sought in the upper layers of the atmosphere, as part of cosmic rays. Large stacks of nuclear emulsions were exposed for many hours

to meet these potential galactic visitors. Their traces were searched for in the surface crystals of meteorites that have travelled through space for hundreds of millions of years.



The search for such extraordinary specimens of nuclear matter has drawn the attention of physicists, chemists, geochemists, and cosmochemists working in research centres across the world. Yet, overall, the results of these experiments to find superheavy elements in nature have so far been negative.

Extensive and meticulous investigations of oceanic concretions, meteorites, mineral ores, and tens of thousands of cubic metres of underground water have shown that, even if the predicted elements do exist in nature, their concentration in the most favourable samples is less than 10^{-12} grams per gram of material examined.

American researchers searching for the 110th and 111th elements – chemical analogues of platinum and gold respectively – have likewise reported no discoveries.

Physicists at the Laboratory of Nuclear Reactions in Dubna, like their American counterparts, continue their search for traces of superheavy elements in nature. Perhaps these searches will yield nothing; perhaps the sought-after nuclei are too short-lived to be observed anywhere except in accelerators, during reactions involving heavy ions.

Yet even if accelerator experiments fail to produce the expected results – if the islands of stability share the fate of Sannikov Land – then theorists will once again have to revise their understanding of the behaviour of superheavy nuclear matter.

While pursuing the fundamental problem of synthesising superheavy elements and pushing towards the limits of nuclear stability, physicists are also solving a number of practical problems along the way. Heavy accelerated nuclei have proved useful not only for inducing specific nuclear reactions, but also for addressing a variety of problems far removed from nuclear physics – such as those

concerning the radiation resistance of materials and certain medical and biological applications.

The simplest in concept, yet highly promising and impressive in its results, is the use of heavy-ion beams as “micro-needles” for producing filters that are extremely fine in structure and unique in their performance characteristics.

In a thin film of mica, glass, or plastic, a heavy accelerated nucleus bores a channel of intense radiation damage. If the damaged regions are then subjected to chemical etching, through-holes are formed in the films.

Using a heavy-ion accelerator, it is possible to produce high-quality molecular-viral nuclear filters with pore sizes ranging from 4×10^{-6} to 10^{-3} millimetres. Even bacteria, whose size exceeds 0.2 micromicrons, cannot pass through such openings.

These nuclear filters, or “nucleopores”, can be used for the cold sterilisation of food products. They will also find wide application in biology and medicine, for example, in the separation of cells of different types.

– One would like to understand: thousands of new, artificially obtained isotopes, new transuranic elements – what are they? A reproach to nature for not having used all her possibilities, or did they once exist, and their absence in nature is somehow connected with the history of the Earth?’

- The second assumption is correct. The modern chemical elements and isotopes are the result of natural selection for stability among the vast family of atomic nuclei that were once born.
- Do nuclei really live and die?
- Yes.

Our planet formed about four and a half billion years ago. The nuclei of transuranic elements and short-lived isotopes simply did not survive to our time. Even uranium-235 has almost “died out”.

The problem of the relative abundance of chemical elements on Earth and in the universe concerned scientists even before the birth of nuclear physics. The percentage content of a given element in nature, at first glance, seems to say little to our minds or hearts. Yet these dry figures immediately convince us that the universe is made of a single material, arranged neatly into the cells of Mendeleev’s periodic table.

It is certain that nature could not have created anything, including our Earth, out of neutrons alone. Only nuclei containing protons could attract electrons and thus turn into atoms of various chemical elements. If some villain – like Engineer Garin or Fantômas – were to invent a device capable of destroying electromagnetic interaction, all matter would disintegrate into electrons and atomic nuclei.

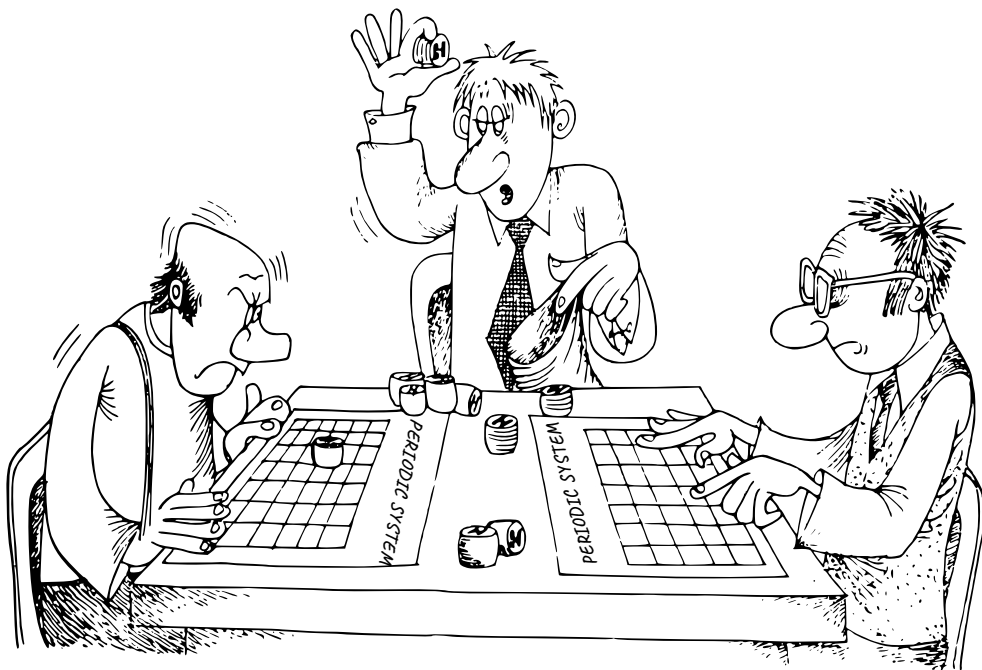
So, what substances make up the universe? The answer is quite simple: it consists of 76 percent hydrogen and 23

percent helium, while the remaining one percent accounts for all the heavier elements that fill the line of stability. What is remarkable is that the relative abundance of these heavy elements is qualitatively the same for cosmic objects as different and distant from each other as the Earth and interstellar space, the atmospheres of planets and distant stars, meteorites, and the Sun.

Everywhere, light elements predominate. Among the medium-mass elements, iron stands out for its relatively high abundance – its nuclei are packed most densely. Oxygen, potassium, and lead, whose nuclei contain a magic number of nucleons, are also found more frequently than others.

Both the natural abundance of elements and their origin are governed by the laws that control nuclear matter. The idea of the evolution of elements was first introduced into science by E. Rutherford. But only nuclear physics – the very field whose foundations he helped to lay – provided the powerful basis needed to tackle the problem of the evolution and origin of chemical elements.

From the scattered arrangement of atomic nuclei along the line of stability, it was as difficult to reconstruct the outlines of the ancient system of isotopes of the chemical elements as it would be to restore the original appearance of the unique cathedral in Yuryev-Polsky, which crumbled in the fifteenth century, using only its surviving stones.



The well-known Soviet art historian G. Wagner, while working on the reconstruction of this ancient architectural monument, was aided by his deep study of the thematic features of the artistic carvings that literally covered every stone of the cathedral. Similarly, physicists, in their quest to understand the origin of the elements, are helped by experiments using heavy-ion accelerators. Artificially induced nuclear reactions, as it were, bring back to us those long-vanished chemical elements and isotopes with un-

usual ratios of protons and neutrons, which, apparently, were abundant among the primordial set of nuclei.

Through the combined efforts of scientists from many disciplines, it has become possible, as if on film, to rewind slightly the natural course of the world's development.

Physicists associate the evolution of elements with specific reactions in which more complex nuclei are born from simpler ones. The evolution of the elements is the result of a definite sequence of nuclear reactions occurring in any corner of the universe where suitable conditions exist.

But the birth of atomic nuclei requires some initial material and a sufficient amount of energy. According to the hot model of the universe's development, at the early stage the temperature and density of matter were so great that they easily supported a continuous dance of emerging and vanishing elementary particles. When the density and temperature of matter decreased significantly, only the stable protons remained from all that motley variety of particles.

At that moment, the world consisted practically of a single chemical element – hydrogen. Even now, roughly twenty billion years later, the universe is composed mainly of this same element.

What extraordinarily unusual conditions, then, were required over the course of twenty billion years to convert even one percent of free protons into neutrons bound by nuclear forces?

It is not so simple to fill the entire periodic system of elements having only hydrogen at hand. Apparently, it all had to begin with the fusion of hydrogen nuclei, for there was simply no other conceivable starting point.

But the reaction of combining four hydrogen nuclei into a helium nucleus is a thermonuclear reaction long known to scientists – it is the process that supplies our Sun with energy. Thermonuclear fusion occurs in the depths of the Sun's matter, where the temperature reaches ten million degrees. Even under these phenomenal conditions, the formation of new nuclei proceeds extremely slowly. One helium-4 nucleus is produced from four protons only after about 330 million years, and in another thermonuclear cycle – even after 14 billion years. This ultra-slow pace of nuclear reactions in the Sun is due to the fact that, even at the Sun's highest temperatures, the likelihood of two protons overcoming their strong electrostatic repulsion remains very small.

The universe, cooled after its expansion, could not provide even the minimal conditions required for the onset of nuclear reactions. Those conditions were created by gravitational forces.

About 18 billion years ago, in regions of space where the mass of matter accidentally exceeded a certain critical value, the first stars began to form. Compressing matter, gravity could heat hydrogen gas to the necessary temperature of several million degrees. The force of gravity ignited a thermonuclear fire right at the centre of a giant “reservoir”

filled with hydrogen fuel. The star thus turned into a blazing furnace in which hydrogen, burning, was transformed into helium.

Hydrogen and helium are the two lightest substances, the first steps in the system of elements. And from these two nuclei alone, nature still had to create another nine dozen more complex configurations of nucleons.

They say that the first step is always the hardest. Once the synthesis of elements had begun, gravitational and nuclear forces, seemingly in complete harmony, carried this complex process forward. As soon as a small portion of hydrogen in the star's core was consumed and the pressure dropped, new gravitational compression raised the temperature of the furnace even higher – up to one hundred million degrees. At such temperatures, the newly produced helium itself became the fuel. Helium nuclei gained enough energy to overcome the higher electrostatic barrier characteristic of the alpha particle.

In the stellar furnace, now fuelled by alpha particles, a wide assortment of products – atomic nuclei – was “baked”. By fusing with one another, alpha particles formed carbon nuclei. Carbon, capturing a helium nucleus, turned into oxygen. Oxygen, repeating the same process, became neon. Finally, when gravitational compression raised the temperature to a billion degrees, carbon itself entered the furnace.

However, the nuclear “combustion” of carbon – the fusion of carbon nuclei – was nothing like the burning of

coal in power station furnaces. In nuclear reactions using carbon fuel, the products 'baked' were already such 'pies and rolls' as the nuclei of magnesium, silicon, and all other elements up to iron.

Further addition of alpha particles or protons only spoiled the 'iron dough' of the nucleus, causing it to fall apart at the very moment of its 'baking'. The periodic table of chemical elements might have remained only half-filled if, fortunately, the depths of the incandescent star had not accumulated a sufficient number of neutrons. The complex nuclei found themselves, as it were, immersed in a bath of these particles.

By capturing neutrons, atomic nuclei began slowly to climb, step by step, up the spiral staircase along the arc of stable isotopes. An additional neutron pushed the nucleus towards an excess of neutrons, away from the line of stability. But after beta radioactive decay – during which an extra proton appeared within the bound group of nucleons – the nucleus returned to the line of stability, now with a higher atomic number.

Of course, this describes the ideal case. In reality, many nuclei, having absorbed too many neutrons, or conversely having shown an aversion to them, must have filled the entire continent of stability up to its very boundaries.

The heaviest nuclei, scientists believe, arise, for example, during a supernova explosion. A star turns into a supernova when, after its internal fuel is exhausted, the pressure within it falls. Sudden gravitational compression leads to

the explosion of the outer shell. The eruption of even the most powerful terrestrial volcano is no more than a spark compared to this cosmic cataclysm. The explosion reaches even the deepest regions of the star. The complex nuclei that have accumulated there over billions of years – the precious product of the star's evolution – are flung outward through raging neutron storms and suddenly find themselves in the tranquil vastness of interstellar space.

In recent years, scientists have been trying to determine how strongly the birth of the heaviest nuclei depends on supernova explosions. It is thought that, during such an explosion, neutrons – like sand in a desert storm that fills every crevice – quickly and in large numbers fill the complex nuclei, pushing them into the category of the heaviest.

Or perhaps, during their long immersion in a stellar “neutron bath”, the heavy elements grow gradually, like crystals forming in a supersaturated solution?

Both of these scenarios for the formation of heavy elements differ somewhat in their final outcome. If the first scenario is correct, nuclei of platinum are most likely to form. In the second scenario, the preference is for elements near lead.

These characteristics should necessarily manifest in the abundance of heavy elements within cosmic radiation. However, the results from examining and analysing nuclear tracks in emulsions exposed both in the stratosphere and on the Skylab orbital station do not yet allow a definitive conclusion. In the distribution of heavy-nucleus

tracks recorded in the stratosphere, a peak appears in the region of platinum, whereas a series of measurements in outer space revealed a predominance of nuclei near lead.

Currently, various countries are preparing an extensive series of experiments to finally resolve the question of the abundance of heavy-element nuclei in cosmic rays, and, consequently, to distinguish between the two models of nucleosynthesis.

Some theorists suggest that a neutron star – the remnant of a supernova – acts as a cosmic factory specialising in the production of heavy elements. According to the idea of the American theorist F. Dyson, “volcanic” activity on a rapidly rotating pulsar, combined with its strong magnetic field, leads to the ejection of fast heavy nuclei into interstellar space.

In the same way, cosmic rays could become enriched with droplets of neutron-rich matter, which, after the beta decay of some neutrons, acquire protons and transform into nuclei of superheavy elements.

Apparently, the entire solar system formed several billion years ago from such “recycled material,” that is, matter that had already passed through the crucible of stellar nuclear synthesis. Otherwise, it would be impossible to explain the presence of heavy elements in a relatively young star like our Sun.

- If the processes that gave rise to all chemical elements ended many billions of years ago, can science demonstrate how this occurred and precisely when the matter constituting the Earth came into being?
- Scientists are establishing this moment on the cosmological timescale with increasing precision, relying on results from particle accelerator experiments, studies of natural radioactivity, and cosmic rays.

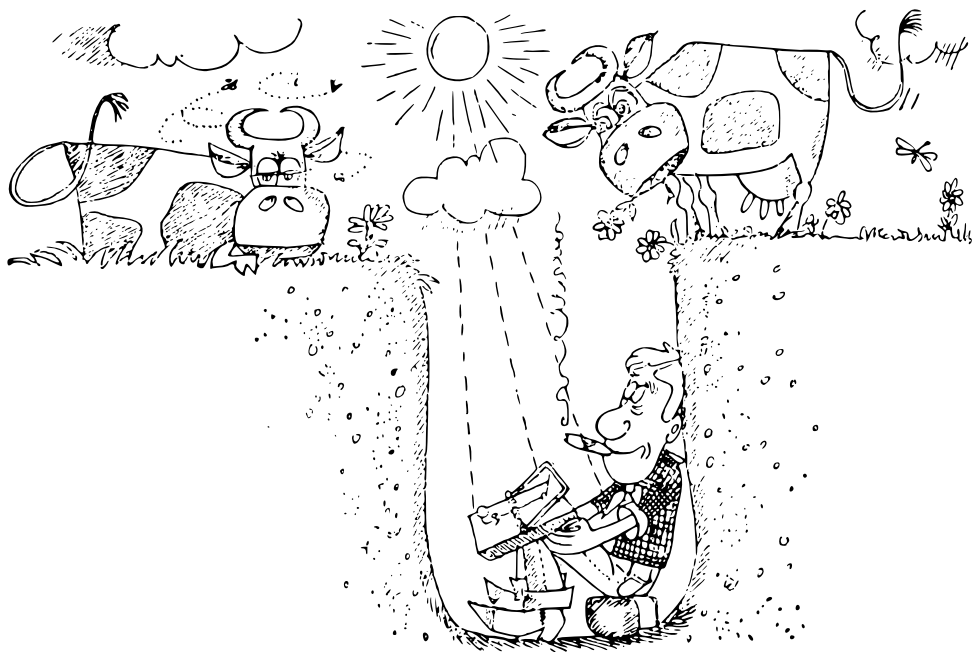
The nearest star to us – the Sun – is at a relatively early stage of its development. Everything we know about it supports the assumption of a properly functioning thermonuclear furnace operating in its depths. “It could not be otherwise,” scientists have been saying for nearly half a century.

However, even today, there is no direct proof of the occurrence inside the Sun of that first reaction in the chain of nuclear synthesis – the fusion of hydrogen nuclei into helium nuclei. The English astrophysicist A. Eddington once said: “There is nothing simpler than a star.” Modern scientists think somewhat differently.

The physics of elementary particles suggested how to obtain the most reliable proof of the Sun’s true activity. To do this, one must detect neutrinos that are born in the Sun during certain reactions of the thermonuclear cycle.

The American scientist R. Davis from the Brookhaven Laboratory in the USA attempted to obtain this proof through

a very complex and expensive experiment using equipment hidden deep underground. The experiment failed. The solar neutrinos seemed to have vanished into the Earth. After the first unsuccessful measurements, the workers who had assembled the installation tried to comfort the scientist, saying: "Don't be upset, Dr. Davis, it was such a cloudy summer." They did not know that there is practically no obstacle capable of preventing the stream of solar neutrinos from reaching Davis's apparatus.



The negative result in the search for solar neutrinos did not shake astrophysicists' confidence in the slow but steady conversion of the Sun's hydrogen reserves into helium-4 nuclei. The absence of neutrinos could be explained without abandoning the idea of thermonuclear reactions, by other, less radical, and sometimes quite original means.

The desire to support with direct experimental evidence the hypothesis of stellar evolution and nuclear nucleosynthesis – that is, the formation of nuclei – never left scientists of various disciplines.

The matter in the inner layers of a star is hidden from earthly observers under seven seals. Only the stellar atmosphere is accessible. Yet it is known that the synthesis of nuclei occurs in the very depths, where the fate of the star is determined. And the chemical composition of its incandescent core could confirm or refute the scientists' assumptions.

But if it is still impossible to look inside even our nearest neighbour – the Sun – then what sense would there be in dreaming of studying distant stars? Nevertheless, astrophysicists turned their attention to stars whose evolution ended in a powerful burst of light – supernovae.

The explosion of a supernova hurled out into space matter that had been “overcooked” in the blazing stellar furnace. Thus arose a unique opportunity to study the chemical composition of a star's deep matter. It was important to compare the content of hydrogen, helium, carbon, and oxygen – the principal participants in the two

thermonuclear cycles – in the shells of supernovae and in all other cosmic objects. In the atmospheres of stars, of the Sun, and of gaseous nebulae, hydrogen predominates; helium is five times less abundant, and carbon, nitrogen, and oxygen are respectively 3,000, 8,000, and 1,500 times less than hydrogen.

In the shells of supernovae, the ratios among these elements should be different. How could it be otherwise? Matter that had spent billions of years in the depths of a star could not have remained unchanged. Moreover, its participation in thermonuclear reactions of the carbon–nitrogen cycle must have left a distinct mark upon it. Irrefutable evidence could come from a “deficiency” of carbon and oxygen, which had been intensely transformed into nitrogen nuclei.

A highly complex analysis of the optical spectra of supernova envelopes yielded exceptionally interesting information. The relative abundance of chemical elements in the matter ejected from the star’s depths differed sharply from the usual distribution of elements in other cosmic bodies. It contained many atoms of helium, nitrogen, and metals, but a deficiency of hydrogen, carbon, and oxygen.

This was a very important result both for the hypothesis of stellar evolution and for the problem of the origin of elements.

Apparently, the synthesis of elements continuously occurs throughout the universe. The radioactive element technetium, detected in the optical spectra of certain stars,

has a half-life of only 220,000 years. Yet the stars themselves are far older, which means that technetium nuclei are being formed in the process of nucleosynthesis occurring within their interiors.

At present, new elements do not arise on Earth in any appreciable quantity. And the fact that long-lived heavy radioactive elements become scarcer as their half-lives shorten suggests that they were formed in remote epochs.

The unstable atomic nuclei of heavy elements now present on Earth – these radioactive clocks of the universe – precisely measure the time separating us from the moment when the solar planetary system was formed and the process of creating its matter was completed.

Nuclear cosmochronology, based on the natural assumption that all heavy elements were formed in roughly equal quantities during nucleosynthesis, allows for very interesting conclusions. Knowing the lifetimes of surviving heavy nuclei and their present abundance on Earth, one can take a fascinating cosmological journey back to the moment when these nucleon systems were born.

Tracing backward the history of any of the long-lived isotopes – uranium-238, thorium-232, or the almost vanished uranium-235 – we arrive at the same point on the time scale, the point corresponding to the maximum abundance of the heaviest isotopes.

Between our time and that point lies an interval of about five billion years. And Earth itself is also about five billion

years old. It seems, therefore, that the synthesis of elements in our Galaxy (in its most intense phase) ended just before the formation of the solar system.

Until quite recently, scientists in their calculations relied on only three types of “experimental” nuclei. But the more varied the material available for study, the more reliable the results.

A few years ago, one of the most exciting “detective” stories in science came to an end, as a result of which cosmochronology gained another example of such a rare isotope-chronometer. In one of the meteorites, researchers discovered a completely unusual quantitative ratio among four isotopes of the noble gas xenon. Scientists suspected that the xenon nuclei in the meteorite had appeared as a result of the spontaneous fission of the isotope plutonium-244, which, owing to its “short” lifetime of about 80 million years, was long considered extinct on Earth.

However, meteorites were formed at the same time as our planetary system, and if traces of plutonium-244 could be found, or if it could be clearly proven that the unique ratio among the xenon isotopes was indeed caused by its fission, then it would be possible to determine, independently and with greater precision, the date of the “smelting” of the Earth’s matter.

The experiment conducted by a group of American scientists to accumulate the fission products of artificially produced plutonium-244 lasted two years. When the isotopic composition of the xenon obtained in this way was

analysed, it turned out to match precisely the result first obtained from the meteorite.

Thus, it was established that plutonium-244 had existed in the solar system at the time when meteorites were formed, and an important ratio between the quantities of uranium-238 and plutonium in that distant epoch was obtained.

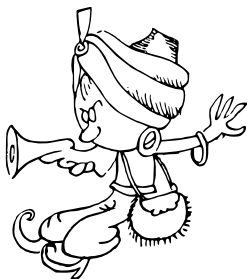
Finally, in 1971, a report appeared in the November issue of the British journal *Nature* announcing the discovery of the isotope plutonium-244 on Earth. Scientists from Los Alamos (USA) found 20 million atoms of plutonium-244 in eight and a half kilograms of the mineral bastnäsite!

This substance – the mineral bastnäsite – had the property of selectively concentrating plutonium. By determining the degree to which bastnäsite was enriched with this element, physicists refined the estimate of the average abundance of plutonium on Earth (which, incidentally, turned out to be vanishingly small).

The unquestionable proof of plutonium's presence in meteorites, together with the near-complete disappearance of this isotope from the Earth's surface, made it possible to conclude that nucleosynthesis ceased literally a few hundred million years before the formation of the solar system.



BREATHE
DEEPER...



5 Breathe Deeper ...

- So, it turns out that when you strike an atomic nucleus with high-energy projectiles, various particles and kinds of information pour out of it. But is it possible to hit the nucleus in such a way that not a single particle flies out of it?
- Nothing could be simpler.
- Then what will happen to it? Will it split, like a nut cracked by a blow, or perhaps it will somehow ring in its own peculiar way?
- The second assumption is closer to the truth. The nucleus will indeed vibrate, like a string displaced from equilibrium, until it returns to its original state.

Everything that exists in nature invariably follows the same pattern dictated by the second law of thermodynamics. Both a giant star and an invisible atom equally strive to maintain the lowest possible energy. Atomic nuclei, too,

prefer the calmest state with the smallest energy reserve. But sometimes they are forced to absorb an additional portion of energy – for example, during a nuclear reaction or radioactive decay, when a daughter nucleus inherits energy from its parent. Such nuclei are called excited nuclei by physicists.

The word “excited”, which physicists are compelled to apply to a nucleus, does not convey the full peculiarity of one of the most intimate processes in that world where quantum laws reign supreme.

One of the most beautiful geysers of Kamchatka cannot be seen at just any time: it either lies dormant or ejects a jet of water and steam high into the air.

Likewise, in the micro-world where energy is always transferred in definite portions, there are no intermediate gradations. The nucleus is either in its ground state with minimal energy or in an excited state.

The atomic nucleus possesses a high energy density. This is the binding energy of the nucleons and their kinetic energy, against the constant background of which the substance of the nuclear drop is formed.

The absorption of additional energy sets in motion certain new springs of the complex mechanism of nuclear forces. That is why the excited nucleus is a very interesting object of study.

The alloy used in the construction of spacecraft is subjected by engineers to special tests to determine its strength

reserve and to detect structural changes.

But how does the energy-saturated nuclear alloy of protons and neutrons behave? What changes arise in nuclear matter at the limit of its strength?

Both experimental and theoretical physicists are trying to find out whether the entire nuclear “drop” begins to move, or whether only one of the nucleons jumps to a higher shell. By observing the first nuclear reactions, experimenters became convinced that atomic nuclei do not absorb just any amount of energy, but only strictly defined portions. Nature has endowed each type of nucleus with an intricate system of reserve states, or levels, to accommodate the acquisition of additional energy.

Knowing precisely which reaction the nucleus has taken part in, one can calculate the excess energy it has received and the angular momentum of its new state. It is also not difficult to determine other parameters of the excited level. But it is far more complicated to find out what specific changes have occurred within the nuclear matter itself.

When a nucleus receives an amount of energy smaller than the binding energy of a single nucleon, the collective of nucleons naturally retains all its members. After a certain time, the nucleus returns to its normal state, emitting a gamma quantum with exactly the same energy as that which it had acquired during the nuclear reaction or inherited from the parent nucleus during beta decay.

But what happens inside the nucleus during those brief

moments when the excess energy is entirely at its disposal?

The nuclear system of nucleons that has received an extra portion of energy, not exceeding about one million electron volts, most often, as experimenters have discovered, uses it only for collective motions of nuclear matter. These can take many forms: rotation of the nuclear “drop”, or oscillation of its surface. At such moments, the drop of nuclear matter apparently assumes the most fantastic shapes, resembling now a melon, now a pear, or even a sphere covered with bumps.

Knowing the reaction in which the nucleus participated, one can calculate the excess energy it acquired and the angular momentum of the new state. It is not difficult to determine other parameters of the excited level as well. But it is much harder to find out what specific changes occurred in the nuclear substance.

When a nucleus receives an amount of energy less than the binding energy of a single nucleon, naturally, the collective of nucleons does not lose any of its members. At the proper moment, the nucleus returns to its normal state, emitting a gamma quantum with exactly the same energy that the nucleus had acquired during the nuclear reaction or had received from a parent nucleus in beta decay.

But what happens inside the nucleus during those few moments when the excess energy is entirely at its disposal?

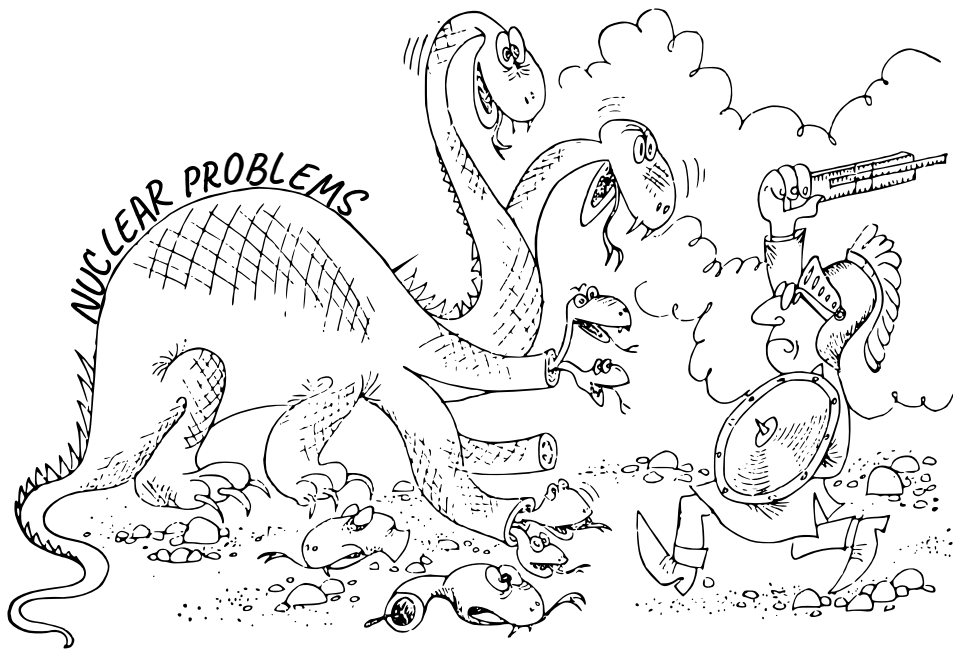
The system of nucleons, having received an additional portion of energy not exceeding one million electron-volts,

most often, as experimenters have found, uses it only for collective motions of the nuclear matter. These may be of many kinds – the nucleus-drop may rotate, or its surface may oscillate. At such moments, the drop of nuclear matter can apparently assume the most bizarre shapes, resembling at times a melon, at times a pear, or even a sphere with bulges.

Until very recently, experiment and theory had gone hand in hand in harmony, and it seemed that nothing threatened their mutual agreement. But quite recently, a new puzzle was posed by the reaction involving the interaction of pi-mesons with nuclei.

At the International Conference on High-Energy Physics and Nuclear Structure, held in 1975 in the American city of Santa Fe, one of the most interesting reports concerned an unexpected result, first obtained by a large international team from the Laboratory of Nuclear Problems at JINR, and shortly afterwards at the Swiss Institute for Nuclear Research. While slowing down pi-mesons in a target substance, experimenters discovered excited nuclei in a state completely improbable for such a situation.

According to physicists, studying nuclei with the help of pi-mesons always resembles a battle with a many-headed mythical creature – the Hydra – since, for every head cut off, two new ones grow in its place. Each new experiment on the absorption of pi-mesons by nuclei raises more problems than it solves.



It was the same this time. The atomic nuclei of the target, placed in a beam of negatively charged low-energy pi-mesons, as usual, captured these particles in accordance with the pi-mesonic atomic ritual—that is, with very small angular momenta. But then something incomprehensible happened to the pairs: instantly freeing themselves from several neutrons, the nuclear drop began to spin rapidly. How then does a pi-meson manage to set the nucleus into such intense rotation without possessing the necessary properties to perform this action?

Lacking, for now, any theoretical support, experimenters are proposing various hypotheses about what their unexpected discovery might mean. Perhaps the high angular velocity of the entire nucleus is imparted by the most peripheral nucleons, which rotate faster than those that, as we already know, absorb the mesons in pi-mesonic atoms.

An excited atomic nucleus does not always expend the received energy, so to speak, on internal processes that require the participation of all nucleons. Sometimes the entire portion of energy is transferred to a single proton or neutron, which can then move to another, unoccupied shell. In such cases, one speaks of single-particle excitation of the nucleus.

Both vibrational, rotational, and single-particle levels of atomic nuclei are often intermingled along the energy scale. At any given moment, the nucleus chooses one or another of its reserve states depending on the conditions under which it receives additional energy.

However, physicists long ago noticed that some nuclei require more energy to move into a single-particle excited state than to move to vibrational or rotational levels. Only when the portion of energy exceeded roughly one and a half million electron volts could these nuclei use it to change the state of individual nucleons.

What, then, accounts for the existence of this mysterious forbidden energy gap before the first single-particle excited state of the nucleus?

For quite some time, not even a vaguely satisfactory explanation could be given – neither through the liquid-drop model nor from the standpoint of the shell model. Only much later was it found that the energy gap between the ground and the first single-particle excited levels was created by the superconducting properties of atomic nuclei.

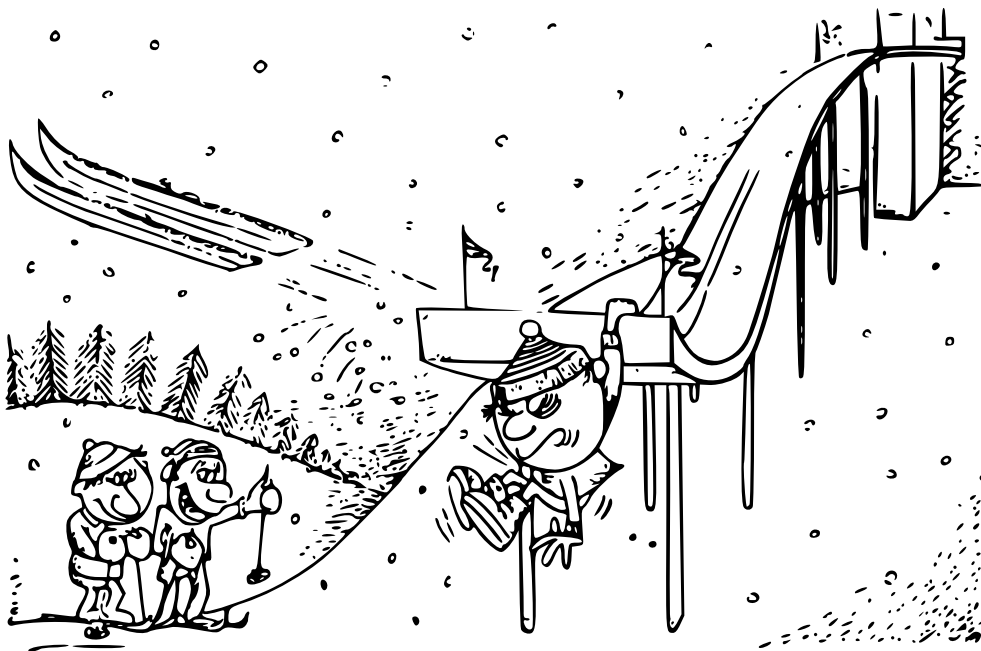
At low temperatures, the superconductivity of a metallic conductor is maintained by conduction electrons that are paired through the vibrations of the crystal lattice. In a similar way, small oscillations of nuclear matter in its ground state additionally glue pairs of nucleons together, apart from the attractive nuclear forces. No single particle within the nucleus can move to another shell without first freeing itself from the influence of its partner. The width of the energy gap corresponds precisely to the energy required to break this bond between nucleons.

- Can an excited nucleus get stuck at its level?
- Imagine, yes, it can. Usually, nuclei, upon discharging, quickly return to their normal state. But sometimes they unexpectedly remain in the excited state for quite a long time.
- Does that mean some new kind of nucleus is formed?

F. Soddy, a young English chemist who, together with E. Rutherford, studied radioactive substances at the University of Montreal, was the first to understand that the world of atoms is far more diverse than the world of chemical elements.

Around the same time that E. Rutherford discovered the atomic nucleus, F. Soddy discovered isotopes – varieties of known chemical elements that differ only in atomic weights. As it was discovered much later, the nuclei of isotopes contained different numbers of neutrons.

By comparing the chemical and physical properties of substances, F. Soddy came to the idea that even isotopes do not exhaust the full diversity of atoms, and that there surely exist still more similar, yet distinct, building blocks of matter.



Atoms of the “higher-order isotopes,” as the scientist called them, were, in his view, supposed to differ only in their radioactive properties. However, among the few radioactive substances known to physicists in 1917, no one could find isotopes of such a higher order, and F. Soddy’s hypothesis remained unconfirmed.

Only four years later, the German scientist O. Hahn — the same who would later discover the fission of uranium nuclei — suddenly found two substances whose nuclei indeed had identical electric charge and mass. Each of these radioactive substances consisted of a special variety of atoms of a single chemical element — protactinium. The two types of protactinium atoms differed only in their radioactive properties: they had different lifetimes.

These were the “higher-order isotopes” predicted by F. Soddy, or, as physicists would say today, an “isomeric pair.” The atomic nuclei of one isotope of protactinium were in the ground state, while those of the other remained trapped in an excited state.

Theorists could say nothing on this matter, for they had at that time no model of the nucleus and no knowledge of its composition. In such circumstances, it was simpler for them to attach no importance to O. Hahn’s discovery. Complete uncertainty regarding isomers prevailed until the discovery of artificial radioactivity.

In 1935, when laboratories around the world were actively engaged in producing new isotopes, Soviet physicists I. Kurchatov, L. Mysovsky, L. Rusinov, and B. Kurchatov dis-

covered a new isomeric pair of nuclei.

I. Kurchatov and his colleagues were conducting experiments to study the properties of radioactive bromine atoms that appeared when stable nuclei were irradiated with neutrons.

The target, consisting of a mixture of two bromine isotopes, was first exposed to a neutron source and then placed near a counter to record radioactive emissions. In every series of measurements, the instrument consistently detected three types of unstable atoms, each with a different lifetime. Yet, since the two stable bromine isotopes in the target could only be transformed into two corresponding radioactive ones, the question arose — where did the third come from?

There could be no question of error. The experiment was so simple that there was simply nothing to criticise, and careful chemical tests confirmed beyond doubt that all three radioactive substances indeed belonged to the chemical element bromine.

Truly admirable was the breadth of thought and intuition of F. Soddy, who had foreseen such a paradox two decades earlier. Relying on the hypothesis of “higher-order isotopes” and on the existence in nature of two types of protactinium atoms, physicists made an important addition to the conclusions of the chemical analysis. Bromine, as it should, possessed only two radioactive isotopes. The third type of bromine nuclei discovered by the experimenters consisted of isomers of its lighter isotope.

The isomeric nucleus of bromine-80 turned out to be the second entry in a long list of unusual excited nuclei. From ordinary nuclei that are temporarily forced to remain in an excited state, isomers differ only by their much longer lifetime.

An excited nucleus, quickly descending to its ground state along the steps of energy levels, sometimes suddenly stops sharply on one of them. This forced pause may last from fractions of a second to several days or even months. This is the isomeric level, a state from which a transition is forbidden by quantum rules.

Only with the help of the shell model did physicists manage to understand the peculiarities of the isomeric state. A nucleus finds itself in such an uncertain position whenever a nucleon, having absorbed all the excess energy, moves to a shell close to the surface. It begins to travel along its orbit with such speed that its strong inertia prevents it from returning to the slower motion it had on the lower shell.

Most likely, this occurs in nuclei whose number of nucleons approaches the magic numbers – 50, 82, and 126. Near these filled shells, there arise peculiar “islands” of isomeric nuclei.

The phenomenon of isomerism in atomic nuclei is direct evidence of the shell structure of nuclear matter.

In 1962, a group of physicists from the Laboratory of Nuclear Reactions at JINR discovered an entirely new type

of isomeric nuclei in certain heavy chemical elements. Around this discovery, debates among theorists have not ceased to this day.

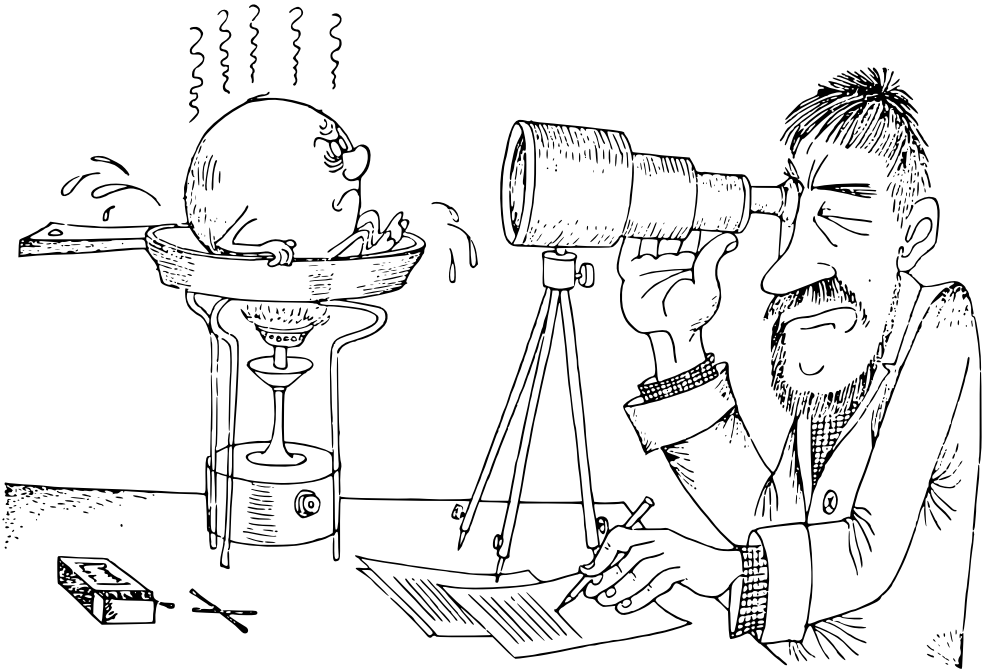
Nuclear droplets containing a large number of nucleons are prone to random shape changes – deformations. Even a slight deformation may so disturb the balance between the nuclear attractive forces and the electrostatic (Coulomb) repulsion between protons that the nuclear drop spontaneously divides into two parts.

For instance, each transuranic element has a characteristic degree of deformation and a corresponding probability of fission. Yet experimenters were astonished to observe that among artificially produced isotopes of fissionable elements, there appeared nuclei in which this event occurred with a probability 10^{26} times greater.

These new “subspecies” of atoms of known elements had the same mass but different lifetimes. Undoubtedly, they were isomers of a very unusual nature.

- One can only marvel at how precisely physicists describe what an atomic nucleus resembles. But do they know what the “overheated” nuclei mentioned earlier look like? Could it be that even in their heated state, nuclei – those objects not of this world” – still resemble the notorious drop?
- Yes. A nucleus saturated with additional energy resembles a drop of heated liquid. One can even

... speak of the evaporation of nucleons from a boiling nucleus.



The heroes of F. Dostoevsky's works often think and act in a state of extreme agitation — in moments of ultimate moral tension, the deepest motives for their actions are revealed.

Scientists understand well that they will never reach

the general laws governing the dynamics and structure of nuclear matter unless they study the behaviour of the nucleus under extreme conditions, particularly during very strong excitations or “overheating”.

A priori, one may say that a nucleus which has received energy exceeding the binding energy of a nucleon will inevitably lose one or several particles.

But what is the nature of an excited nucleus during that brief interval when it no longer has the right to possess one or several nucleons, yet those nucleons have not entirely broken their bonds with the collective of nuclear particles? One can judge such an unusual quasi-bound — that is, seemingly bound — state of the nuclear system by knowing how it was formed, how long it existed, and how it subsequently returned to its normal state.

In many nuclear reactions where the participating nuclei received energies of tens or even hundreds of millions of electron-volts, experimenters observed seething, overheated nuclei. Identifying them was not difficult, primarily because of their extraordinarily long lifetime — by nuclear standards. The boiling of the droplet-like nucleus lasted up to 10^{-14} seconds, until the evaporation of nucleons from its surface brought it to a calm state.

Physicists have firmly understood that when a nucleus absorbs a large portion of energy, it turns into a system of rapidly and chaotically moving particles. The delicate bonds between nucleons — which, at lower excitation energies, gave rise to collective motions within nuclear matter

— seemed to be entirely broken. The nucleus no longer resembled a structure of light spheres connected by tiny springs, capable of complex, coordinated oscillations.

But once synchrotrons — electron accelerators — appeared, scientists' ideas about highly excited nucleonic systems changed dramatically. Target nuclei were found to absorb electromagnetic radiation from the synchrotron with high probability. Gamma quanta with energies of 10-25 million electron-volts were absorbed particularly readily. The nucleon system then entered a quasi-bound state, though one completely unlike the boiling of a nuclear droplet.

This was astonishing news even for physicists well acquainted with the marvels of the microworld. When given the same amount of energy — but, so to speak, served under a different “sauce” — the nucleus reacted quite differently. During electromagnetic interaction with gamma quanta or electrons, the nucleus entered a special excited state lasting about 10^{-20} seconds, in which all the protons oscillated relative to the neutrons.

Gamma quanta and electrons, infinitely more delicate in raising the nucleus's “tone” than strongly interacting particles, were long regarded as the only suitable tools for such a subtle operation. Yet an even more refined method of introducing energy into a nucleus exists — through the weak interaction. When a nucleus absorbs a mu-meson from a mesoatomic orbit, it almost imperceptibly acquires about 20 million electron-volts.

For a long time, scientists assigned the nucleus only a passive role – that of a supplier of protons for the well-known reaction of these particles with mu-mesons, which proceeds according to the laws of weak interaction. The number of theoretical and experimental studies devoted to the nuclear muon-capture reaction exceeded a hundred when the first doubts arose about the correctness of this view. Upon improving the accuracy of their calculations, physicists discovered that the experimentally determined probability of the muon-capture reaction differed almost twofold from the value predicted by theory. This contradiction demanded a radical rethinking of the very nature of the process.

Thus, in the autumn of 1963, at an inter-university conference in Uzhhorod, a group of theorists from Moscow State University and the Laboratory of Theoretical Physics of the Joint Institute for Nuclear Research, led by Professor V. Balashov, presented a fundamentally new interpretation of what occurs inside the nucleus during muon capture. This group of scientists boldly asserted that the nucleus itself plays the decisive role in distributing the energy among all participants in the reaction and in determining how its own share is absorbed.

As in the case of electromagnetic interaction during the absorption of gamma quanta from a synchrotron, the nuclear system of nucleons entered, for about 10^{-20} seconds, a quasi-bound excited state with complex collective oscillations of some groups of particles relative to others. According to the theorists, the rapid oscillation of nucleons

– revealing the remarkable elastic properties of nuclear matter – arose from the alternating excitation of all nucleons within the nucleus.

The new hypothesis could be tested in only one way – by detecting groups of neutrons whose appearance in this reaction it predicted.

Physicists from the Laboratory of Nuclear Problems at the Joint Institute for Nuclear Research, led by Candidate of Physical and Mathematical Sciences V. Evseev, undertook the search for neutrons emitted from a target irradiated by mu-mesons.

An international team of Soviet and Polish physicists prepared a special setup for the synchrocyclotron to detect neutrons in the reaction of meson capture by atomic nuclei. In a transparent crystal of stilbene – a hydrogen-rich substance – a passing neutron transfers its energy to the nucleus of a hydrogen atom, that is, to a proton. The instrument responds instantaneously to the moving charged proton: a flash of light appears in the stilbene, which, amplified by a special device – a photomultiplier tube – is converted into an electric pulse.

However, a flash of light could also appear in the crystal if any stray charged particle entered it. Therefore, the electrical impulses from the flashes in the detector were subjected to the strictest control by unique electronic circuits specially designed for this experiment. From the shape of the impulse, these circuits reliably distinguished protons from background particles. Then an electronic

pulse analyser determined the energy of these protons, and a computer, following a special programme, reconstructed the neutron spectrum from the measured energy spectrum of the protons.

The very first experiments on the accelerator proved successful. When targets made of sulphur, calcium, or oxygen were placed in the beam of mu-mesons, the Dubna physicists, with great excitement, detected the long-awaited groups of neutrons. The experiment fully confirmed the theorists' expectations.

Speaking at the International Conference on High-Energy Physics and Nuclear Structure in Dubna, Professor V. Balashov said: "It is natural for theorists to be imaginative. But I never thought that experiments on mu-meson capture by nuclei would be carried out with such high precision that they could be directly compared with theory."

The discovery made by the Dubna physicists, along with the experimental results obtained in other laboratories, confirmed a very important regularity for nuclear physics. In electromagnetic, weak, and even, with small probability, strong interactions, atomic nuclei are formed that expend all their additional energy solely on the collective motion of their particles. Collective oscillations of nucleons at high excitation energy are a universal property of nuclear matter, connected with the special nature of nuclear forces.

- “At first,” someone remarked, “physicists rejoiced that they had learned how to extract energy from nuclei, and now – for some reason not at all clear – they rejoice when nuclei absorb it.”
- “The study of excited nuclei has great fundamental significance for science,” came the reply, “for it enriches our understanding of nuclear forces. Yet isomeric nuclei, possessing the ability to retain their excess energy for quite a long time, may also be used for practical purposes.”
- “I have never heard of an “accumulator” based on excited isomeric nuclei.”
- “Naturally, you have not. As a long-lasting accumulator of nuclear energy, radioactive isotopes proved to be more advantageous. But isomers became extremely useful once it became possible to establish communication using gamma quanta between identical nuclei.”

Until now we have spoken, and continue to speak, about problems directly related to atomic nuclei. But it is now essential to recall a long-known phenomenon in the world of atoms – the selective, or, as physicists call it, *resonant absorption* of photons with a definite energy. Light emitted by an excited atom is most readily absorbed by another atom of the same chemical element. This is the natural behaviour of all quantum objects.

Relying on the law of conservation of energy and the concept of excited nuclear states, physicists, some forty-

five years ago, attempted to discover a resonant connection between nuclei through photons of high energy (also called *gamma quanta*).

However, the gamma quanta emitted by a nucleus returning to its normal state — already, so to speak, “tested” and ready — unexpectedly proved entirely unsuitable for exciting other nuclei of the same kind.

Of course, at that time experimental technology was very primitive — though the idea of the experiment itself was simple. The setup was arranged as follows: the source contained isomeric nuclei, and the target — exactly the same nuclei, but in their ground state. Behind the target was placed a gamma-quantum counter. By the counting rate in the detector, it was possible to tell whether the nuclei of the target absorbed the resonant gamma quanta or not.

Neither in the first, nor in the second, nor even in the tenth attempt was it possible to detect this phenomenon. The gamma quanta passed freely through the target and reached the counter.

For fifteen years, scientists struggled to solve the mystery of this phenomenal and persistent non-contactability of identical atomic nuclei. They struggled until the cause of this puzzling behaviour was finally uncovered — uncovered, not eliminated.

Both the excited nucleus and the excited atom are, in essence, single-wave transmitters. A light quantum of a

fixed frequency, emitted by an atom of a chemical element, can be received only by a single quantum receiver – an atom of the same element. Similarly, a nuclear gamma quantum, which also corresponds to a wavelength of a definite frequency, can excite only an identical stable receiver nucleus.

Atomic and nuclear receivers and transmitters have no knobs for tuning. For atoms, this was not needed: photon communication between them worked perfectly. But the nuclear receiver did not accept nuclear gamma quanta and remained silent.

In ordinary radio equipment, tuning can go wrong because of a burnt-out component. But what could possibly burn out inside a nucleus?

The laws of quantum mechanics – in particular, Heisenberg's uncertainty principle – define the range of energies within which resonance should be observed, both in atoms and in nuclei. This range, called the width of the resonance line, is inversely proportional to the lifetime of the nucleus in its excited state. For example, in the case of iron-57 nuclei, which hold their excess energy for about 10^{-7} seconds, the line width equals 10^{-8} electron-volts.

In isomeric nuclei, the lifetime and the energy interval of emitted photons – within which resonance might occur – were almost the same as in atoms. Yet it was still impossible to establish gamma communication between the nuclei.

Finally, in 1945, the young Soviet scientists I. Barit and M. Podgoretsky opened everyone's eyes to a circumstance that had previously been overlooked. The law of conservation of energy could guarantee the success of nuclear communication via gamma quanta, but it could also harshly punish physicists for an oversight committed in relation to it. And the oversight was quite serious. For some reason, in their calculations, the scientists did not account for the small amount of energy that the nucleus received at the moment of recoil when the gamma quantum was emitted.



This extremely complex system of elementary particles, bound together by unique nuclear forces, when emitting a gamma quantum, claimed its share of recoil energy just like an ordinary macroscopic object.

The energy of a gunpowder explosion is divided between the bullet and the rifle in exact accordance with their masses: the light bullet receives the greater part, but the rifle also gets a bit. The excess nuclear energy is distributed in exactly the same way between the nucleus and the gamma quantum: almost all the energy goes to the photon, while the nucleus receives only a negligible fraction.

It was not that the recoil of the nucleus had been forgotten, but rather that no importance had been attached to it. Everyone was reassured by the qualitative conclusion that the energy of the gamma quantum remained practically unchanged. The recoil energy had never been taken into account in atomic resonance either; its value, approximately 10^{-10} electron-volts, was far smaller than the width of the resonance line and could not disturb the photon connection.

However, there was one colossal difference between atomic and nuclear transmitters: they operated in entirely different energy ranges. Atoms emitted energy on the order of several electron-volts, while nuclei emitted millions of electron-volts. It is clear that in the division of energy between each of these micro-objects and the corresponding quanta of electromagnetic radiation, the nucleus received

an incomparably greater share than the atom.

In nuclear gamma resonance, one ten-millionth of the energy taken by, for instance, the same iron-57 nucleus equals roughly 10^{-3} electron-volts. Though this portion is itself extremely small, it is nonetheless 10^5 times greater than the entire interval of resonance energy.

The recoil of the nucleus, which physicists had previously dismissed as negligible since it only slightly altered the energy of gamma quanta, at the same time completely deprived them of the ability to maintain resonant gamma connection with other nuclei. What kind of communication could there be under such conditions? To seek nuclear gamma resonance in these circumstances was like trying to receive, say, a Sydney radio station in Moscow during severe fading.

Yet under special conditions, scientists nevertheless managed to establish gamma connection between nuclei. A nucleus experiencing recoil and the gamma quantum emitted from it, having slightly less energy—or, equivalently, a lower frequency—move in opposite directions. Here we encounter the Doppler effect, long familiar to physicists.

The acoustic version of this effect is probably known to everyone. The whistle of a departing locomotive sounds lower in pitch than that of the same locomotive approaching the platform. The frequency of the waves propagating in the direction opposite to the motion of the sound source decreases.

Fortunately, the Doppler effect can be counteracted. If the source containing the excited isomeric nuclei is moved towards the target, one can compensate for the change in frequency of the gamma quanta that strike it.

Indeed, after calculating the velocity required to move the emitter, physicists nearly gave up all hope of making use of nuclear gamma resonance. It turned out that the recoil could be compensated only by moving the nuclei at the speed of sound.

Despite such stringent conditions, experimenters managed to register resonance at the very moment when excited mercury nuclei, carried by an ultracentrifuge arm, swept past a stationary mercury target and a gamma counter. It can hardly be said that this was a particularly convenient method for studying gamma resonance.

However, those who could not endure the howl of the centrifuge could choose another approach – for instance, heating the emitter nuclei to several thousand degrees. In that infernal heat, the nuclei also acquired the velocity required to compensate for recoil. But hardly any laboratory could erect its own blast furnace for such an experiment.

And then suddenly everything changed for the better. The centrifuges were discarded, and the nearly solar fire raging in laboratories was finally extinguished.

In 1958, the German physicist R. Mössbauer demonstrated how easily and simply one could observe gamma resonance if certain precautions were taken beforehand to

eliminate nuclear recoil. The young scientist became the only person in the world to use the full expression nuclear gamma resonance without recoil instead of the shorter term adopted by all to describe this phenomenon – the “Mössbauer effect”.

A research fellow at the Max Planck Institute in Heidelberg, R. Mössbauer, received from his supervisor a dissertation topic entitled “Investigation of the Resonant Absorption of Gamma Quanta.” The original plan was to study the properties of this phenomenon in the traditional way –by strongly heating the emitter and absorber nuclei. But the doctoral candidate chose his own, original path to solving the problem set before him. He realised how one could, without heating, almost completely eliminate the nuclear recoil. R. Mössbauer tested his idea experimentally and described it in his dissertation for the degree of Doctor of Philosophy. At the time of publication, he was twenty-nine years old, and three years later he received the Nobel Prize in Physics in Stockholm.

R. Mössbauer was neither a magician nor a sorcerer and could not repeal the laws of nature. The scientist understood how to influence the distribution of energy between the gamma quantum and the nucleus – in favour of the gamma quantum.

Everyone knows that if one props a rifle against a wall, the recoil upon firing will be negligible. The mass of the rifle, effectively increased by the mass of the wall, becomes so great that almost all the energy released by the explosion

of the gunpowder goes to the bullet.

“Of course,” said R. Mössbauer in a lecture delivered several years ago in Moscow, “it is not so easy to fasten nuclei to a wall. However, one can attempt to do so by taking, instead of a single atom in the gaseous phase, a collection of atoms arranged in the form of a crystal.”

The chemical forces firmly bound the atoms containing the excited isomeric nuclei to the crystal lattice, which acted as a kind of wall and practically eliminated the recoil of the nucleus during the emission of gamma quanta.

The Mössbauer effect soon found wide application. With its help, it became possible to measure incredibly small changes in the energy of gamma quanta. The sensitivity of this method far surpassed anything previously achieved in any branch of physics.

- All this is very interesting, but what has the Mössbauer effect to do with the use of isomeric nuclei?
- The most direct relation. Without the discovery of this effect, one could not even have dreamt of creating a nuclear laser.
- A laser? Can excited nuclei really be controlled?
- Physicists hope to obtain a beam of nuclear photons through recoil-free gamma resonance.

The French scientist A. Poincaré once wrote that “every truth is destined to enjoy one moment of triumph between the infinity during which it is considered false and the in-

finity during which it is considered trivial.” Yet the theories created by one of the greatest scientists of the twentieth century, A. Einstein, somehow stand apart from that long succession of hypotheses that rather quickly outlived their moment of triumph.

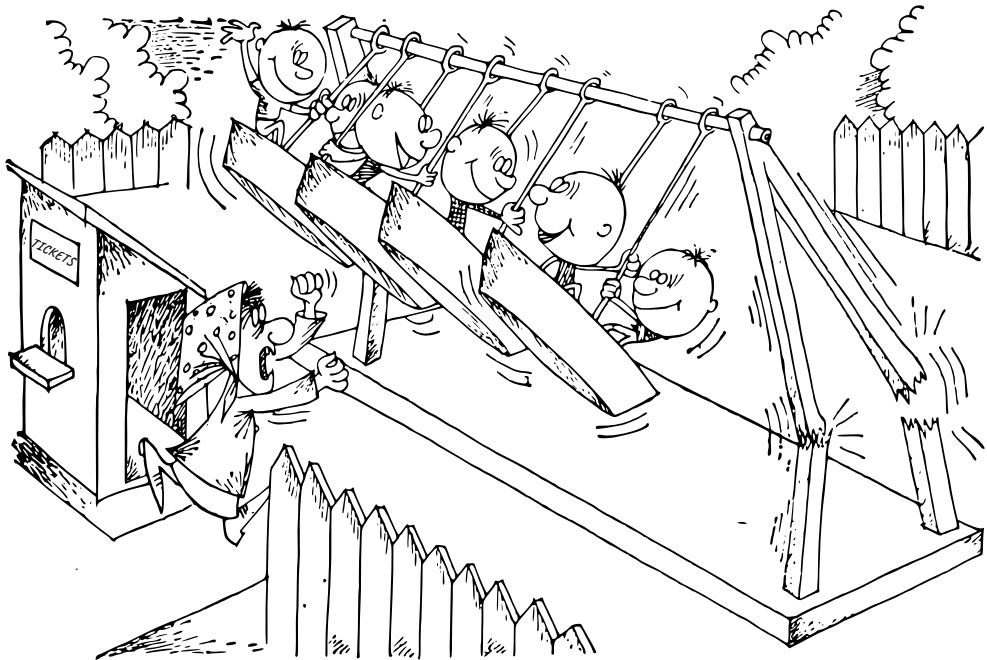
An interesting result obtained by Einstein, at the time when he was studying the problem of emission and absorption of photons, was realised only sixty years later in one of the most remarkable instruments of our age – the laser.

Excited atoms usually emit quanta of light as incoherently as musical instruments sound when musicians are tuning them before a concert. But when the maestro raises his baton, there arises a melody – the result of the coordinated playing of the entire orchestra.

The orchestra of excited atoms, as predicted by theory, can be controlled by electromagnetic radiation of the same frequency as the light emitted by atoms returning to their normal state. A multitude of pre-prepared excited atoms, obeying the command to return immediately to their ground state, simultaneously release their excess energy.

The remarkable English physicist M. Faraday, reflecting on precious stones—rubies and diamonds—wrote: “None of these gems can rival the brilliance and beauty of the charm of flame.” The red beam from a ruby laser equals the flame in beauty and charm, and in the “quality” of its light, it leaves the flame far behind. All the atoms of the

laser work in perfect harmony, as one.



If we could observe each of the laser's atoms, we would see that their oscillations are synchronised in phase. Therefore, the radiation of all atoms merges into a single wave. Such light is called coherent.

At the very beginning of our century, nothing was yet known about atomic nuclei, and A. Einstein, in his reflections, had in mind only atoms. But the conclusions of

his theory are entirely applicable to the emission and absorption of nuclear gamma quanta—that is, photons with energies millions of times greater.

In a gamma laser, or *gaser*, as physicists call it for short, pre-excited atomic nuclei must operate, producing controllable electromagnetic radiation of the same supreme quality as in an optical laser.

The marvellous laser light has already brought a revolution to many fields of science and technology. An even greater revolution, for example in biology, will be produced by the coherent electromagnetic radiation of a gaser, with a wavelength smaller than the size of an atom. To penetrate the secrets of living matter, scientists must be able to observe the structural details of protein and gene molecules. With the help of laser gamma quanta, it will become possible to study even the movement of individual macromolecules in living tissues.

The synchronous radiation of excited nuclei will make it possible not only to obtain a three-dimensional image of a DNA molecule within a cell but also to record a three-dimensional film showing the process of DNA duplication and protein synthesis in ribosomes. A gaser can produce an extremely short pulse of radiation—up to 10^{-15} seconds. Therefore, when illuminated by gaser light, each frame of this unique film could show molecular thermal vibrations “frozen” in time. Why, then, has a nuclear gamma laser not yet been created? The creation of a gaser is an undertaking of extraordinary complexity. It will require the combined

effort of many laboratories and institutes, the utmost intellectual exertion, and the use of the latest advances in technology.

They say that a device, an experiment, and the physical problem it solves are the bread, love, and imagination of an experimental physicist. And if theorists are the ones who most often indulge in imagination, and their demands for love keep growing, then the bread forever and freely belongs to the experimentalists. At present, scientists are widely discussing the main problem that must be solved before proceeding directly to assembling the most complex apparatus. There is still no clear opinion on how to collect a sufficiently large number of excited atomic nuclei in the working substance of a gaser.

In a ruby laser, chromium atoms are easily excited by the light from a powerful discharge lamp, but atomic nuclei cannot be excited by light. For that, nuclear reactions are required.

In 1961, Soviet physicist L. Rivlin was the first to propose a scheme for creating a nuclear laser based on Mössbauer emission without recoil. The crystal is more than half enriched with long-lived excited nuclei—isomers. And it is enough for just one to “discharge” for its gamma quantum to serve as a signal for all the other nuclei, and the gaser orchestra would start playing. But alas... instead of an enchanting melody, we would hear the cacophony that might be produced by the well-known quartet from Krylov’s fable.

The excitation of nuclei by neutrons, their extraction from the target, and crystallisation take at least several days. Isomers with such a lifetime do exist, but the width of their resonance line is so small that distortions become noticeable, caused by defects in the crystal lattice. These distortions, different for each nucleus, severely disrupt the nuclear gamma resonance.

Wouldn't it be better to make a gaser using short-lived isomers, as proposed by the Soviet scientists V. Goldansky and Yu. Kagan? That would immediately remove worries about crystal-lattice defects and the weak magnetic interactions between nuclei, which also shift the energy of resonant gamma quanta. Their influence would be essentially negligible given the line width corresponding to excited-nucleus lifetimes on the order of 10^{-2} - 10^{-6} seconds.

But how can one possibly carry out all the necessary preparatory procedures in such a short time?

It seems impossible to provide the nuclei with neutron-capture reactions, isolate the excited isomers, and assemble them into the crystalline medium of a gaser in time. To avoid running out of time, physicists propose skipping the last two operations and concentrating all attention on a single one, which is as follows.

First a crystal is prepared containing the nuclei that are to be converted into isomers. Then an extremely intense neutron flux – approximately the kind produced in a nuclear explosion – excites the atomic nuclei in millionths of

a second. Is the gaser ready then?

No. The trouble is that neutron irradiation is destructive for the crystal: it overheats and may be ruined. Therefore it is absolutely necessary to remove the gaser's working substance from the neutron-irradiation zone – the material in which the gamma quanta will be emitted.

Thus one more operation is added to all the previous ones, and it must be completed in the same millionths of a second. One must either transfer the isomeric nuclei created into another crystal, or pump into that second crystal all the precious energy accumulated during the neutron irradiation.

Of course, energy is not water that is pumped through pipes, but in this case no wires are needed either – the ones normally used to supply electrical power. The isomers, by means of resonant gamma quanta, can transfer their energy to like stable nuclei of the second crystal and turn it into a gamma-laser ready for operation. Discussions are still underway about the problem as a whole and about the individual operations. Working with long-lived isomers is much more convenient, and every possibility to reduce distortions of the resonance-line width is now being considered in detail.

The dilemma faced by those working on the problem of the gamma-laser – either a long lifetime of isomeric nuclei or an extremely narrow resonance line – no longer seems insoluble today. Crystallography specialists have achieved significant progress in growing so-called defect-

free crystals. And physicists propose shielding against distortions caused by weak magnetic interactions between nuclei in the crystal lattice with the help of an external radio-frequency field.

However, perhaps the first gamma-laser to operate will be one whose parameters are selected according to the principle of the golden mean. Such a version of the gaser, employing the Mössbauer effect, was proposed by the Soviet scientist V. Letokhov. In his view, in a future device the gamma quanta should be emitted by isomers with lifetimes neither too long nor too short — from 0.1 second to 10 seconds. Exciting these isomeric nuclei does not require extremely powerful neutron fluxes. The quantity of isomers necessary for the gaser's operation can be obtained with existing nuclear reactors. However, unlike the previous versions, in this case the working substance of the gaser must undergo procedures so complex that no material is subjected to anything similar even in the most sophisticated industries.

First of all, it is necessary to extract the excited nuclei from the target material that has been exposed to the neutron flux. And the fastest method appears to be an almost fantastic one, based on the latest achievements of science and technology — something that the natural philosophers of the seventeenth century would have simply called “dematerialisation.”

A short, powerful laser beam breaks the target into individual atoms. Two more lasers, their beams directed at

the gaseous stream of the evaporated mixture, selectively ionise the atoms containing the excited isomeric nuclei. An electromagnetic focusing system easily collects these ions, and the excited nuclei settle — “materialise” — on a charged filament or film. Instant crystallisation completes this complex process of preparing the working substance of the gamma-laser.

V. Letokhov believes that the current state of nuclear and laser technology already allows for the practical solution of problems related to the development of such a gaser.

Both experimental and theoretical studies of “reserve” nuclear energy levels, which previously seemed to have purely theoretical significance, have proved to be of great necessity. Without the knowledge obtained by spectroscopists, it would be impossible to build the unique instrument of the future — the nuclear gamma-laser.

At present, a broad programme is being proposed for the study of problems in various fields of science and technology that are directly related to the production of coherent gamma radiation. It is possible that in the very near future new and fundamental ideas will emerge, the realisation of which will accelerate the development of a concrete project for a nuclear gamma-laser.

The appearance of gasers in laboratories will open new horizons for researchers of atomic nuclei. Ordinary lasers have already stimulated the development of a new branch of science — so-called nonlinear optics. New phenom-

ena have been discovered in the interaction of laser light with matter. Powerful laser beams, passing through substances, transform them and thereby alter the conditions of interaction between photons and atoms or molecules.

Apparently, gasers will lead to the creation of an analogous scientific field – nonlinear nuclear physics, which will study nuclear processes occurring under the influence of a powerful flux of perfectly identical gamma quanta.

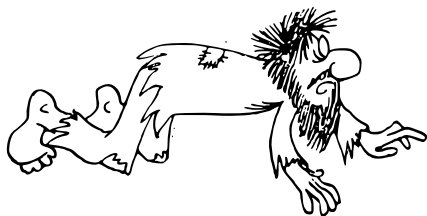
More than once, physicists have discovered in natural conditions – in space – phenomena that they could not at first reproduce or detect on Earth. For example, the chemical element helium was first identified in the solar spectrum (the Greek word *helios* means “solar”). Many elementary particles, including the first messengers of the antimatter world – positrons – were first detected in cosmic rays.

It has been proven that masers – amplifiers of radio waves in the centimetre and millimetre ranges – “operate” in space. And perhaps the Galaxy also sends us astonishing synchronous gamma radiation, which no one has yet observed on Earth?

Not long ago, scientists recorded enormous bursts of gamma rays in certain regions of outer space, lasting from fractions of a second to one minute. The extraterrestrial gamma quanta had energies ranging from 0.05 to 1.5 million electron-volts. The mechanism behind these bursts remains unclear – but perhaps it is a natural gamma laser at work: a gaser!



A TALENTED IMITATOR



6 A Talented Imitator

– The nucleus turned out to be a very complex thing, and apparently physicists, by studying elementary particles, are striving for simplification? – At first, it seemed so. But gradually, in the behaviour of elementary particles, such bottomless depths of the unknown and the extraordinary were revealed that physicists studying elementary particles once again turned to nuclear physics. – That is not clear. In my opinion, the nucleus is as unlike a single particle as a complex multicellular organism is unlike an amoeba? – However, that very nucleus, when accelerated to high energy, is capable of imitating an elementary particle.

In October 1970, at a meeting of the Academic Council of the Joint Institute for Nuclear Research in Dubna, Corresponding Member of the USSR Academy of Sciences A. Baldin spoke about the first experimental results ob-

tained in a new field of science – relativistic nuclear physics, born in the Laboratory of High Energies.

The synchrophasotron of this laboratory, created under the direct guidance of Academician V. Veksler, had long held the position of ex-champion in the energy of accelerated protons. Some of its structural features attracted researchers, and they decided to rejuvenate the veteran synchrophasotron.

Engineers and scientists from socialist countries brought to life a clever idea proposed by a group of specialists, transforming a morally obsolete giant installation into the world's first accelerator for producing relativistic atomic nuclei, that is, nuclei moving at speeds close to the speed of light. The energy that an atomic nucleus gains in this accelerator is greater than that of a proton by as many times as its electric charge exceeds the proton's charge. Thus, in principle, a calcium nucleus can be accelerated to 200 billion electron-volts.

This new scientific field, whose theoretical and then experimental foundation was first created at the Joint Institute for Nuclear Research (JINR), helped unite into a single system such distinct domains of microscopic investigation as nuclear physics and the physics of elementary particles.

Previously, we spoke only about the applied, so to speak, links between nuclear physics and high-energy particle physics. Essentially, these were limited to the use of elementary particles in experiments aimed at revealing the structure and properties of nuclear matter.

In recent years, physicists studying elementary particles have noticed a deep analogy between nuclear reactions at high energies and the reactions involving elementary particles. They therefore turned to relativistic nuclear physics for help in solving the most difficult and most important of their problems – the creation of a theory of strong interactions.

Even a superficial acquaintance with the results of research on elementary particles reveals one striking paradox: most reactions caused by accelerated particles are accompanied by strong interactions between their participants, yet the theory of this interaction remains the least developed.

Since the time of E. Rutherford, who was the first to observe the behaviour of an alpha particle and an atomic nucleus at close range, physicists have done little else but collide nuclear particles to obtain information needed to construct a theory. They believe that they will uncover all mysteries and solve all riddles of strong interaction if, for example, they can make protons approach each other as closely as possible. Experimenters strive to achieve this by imparting to protons, through accelerators, ever greater energy.

But the world of elementary particles, which cannot exist outside its nourishing environment of immense energy, responds very sensitively to any change in that energy. Predictions about the behaviour of particles in a new energy range, based on observations made at lower energies,

rarely come true.

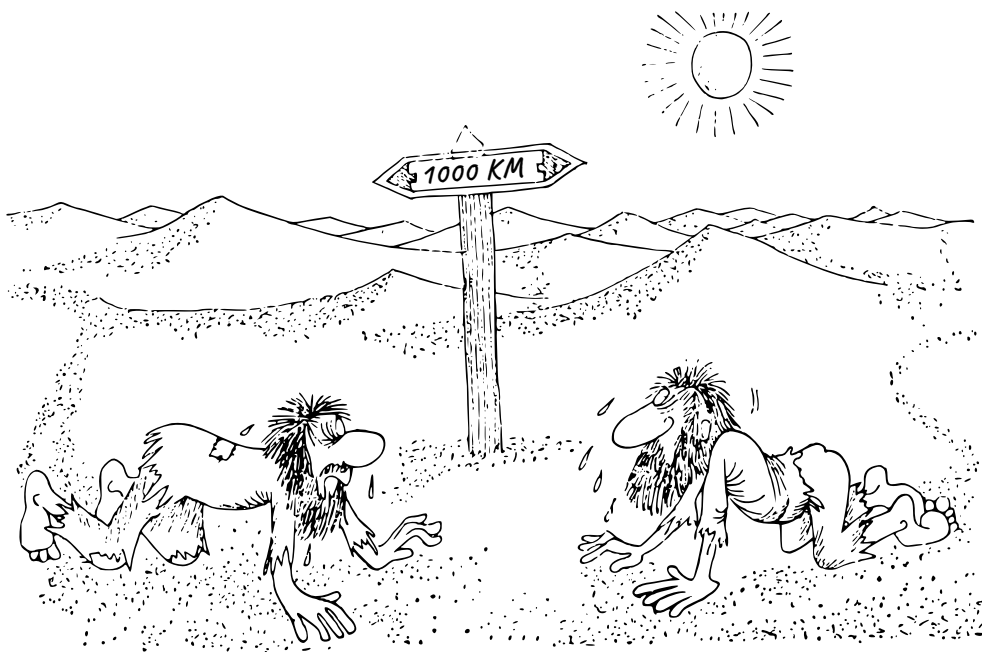
Protons moving at speeds close to that of light, as a rule, encounter entirely different possibilities than do protons moving at low speeds. This means that experimenters are dealing each time, as it were, with a completely unfamiliar object that must be studied anew.

The desired goal – the discovery of the laws governing strong interactions – recedes ever farther as one approaches it, just as the horizon recedes before a weary traveller. And today, the description of what seems the simplest event – the encounter of a high-energy proton with another proton – remains one of the most challenging problems in high-energy physics.

What, then, has turned the collision of two nuclear particles into such a prolific source of difficult questions?

Powerful accelerators speed up protons so greatly that their corresponding wavelength, according to quantum mechanics, becomes three orders of magnitude smaller than the size of the particle itself. This, in turn, makes the nuclear reaction highly sensitive to the internal structure of the protons: in the interaction of two particles, one essentially observes the interaction between their constituent parts.

How, then, do protons of enormous energy perceive one another as they approach?



That is precisely the issue – physicists do not yet know what structure hadrons possess (as we have already noted, hadrons is the general name for all strongly interacting particles), and therefore cannot imagine what will actually happen during the collision of merely two elementary particles.

Experimental physicists conscientiously perform their task – painstakingly collecting, bit by bit, scattered and fragmentary information about the behaviour of hadrons.

Theoreticians, on this basis, construct models of hadron structure and simulate the reactions of elementary particles at high energies.

The circle of knowledge – observation, reflection, prediction, verification – closes upon itself, revealing the truth. At present, it is this: just as the nucleus sometimes behaves like a drop of nuclear matter and at other times like a cluster of independent nucleons that have come together for some reason, hadrons too occasionally exhibit completely opposite properties.

A group of Dubna physicists led by Doctor of Physical and Mathematical Sciences V. Nikitin first carried out experiments at the Serpukhov accelerator, and later, together with American scientists, at the accelerator in Batavia (USA), studying the same reaction – the elastic scattering of high-energy protons on protons. This means an interaction between particles in which the incoming proton expends all its energy only on changing the velocity of the target proton – as happens, for instance, when one billiard ball strikes another.

The purpose of these experiments was to measure the radius of the proton at various collision energies. The target – a jet of gaseous hydrogen – was irradiated with protons possessing energies from 10 to 400 billion electron-volts. The results turned out to be somewhat unexpected: the size of the proton increased with the increasing speed of the colliding particles.

And this conception of the proton as something mono-

lithic, occupying a greater or lesser yet quite measurable region of space, must now be reconciled with an entirely different image of this particle. This new image arises from the study of another variant of the same reaction – the inelastic scattering of very fast protons on protons. In this latter case, the apparatus recorded protons that were deflected at large angles and had lost a substantial portion of their energy. That energy was transferred to the target proton, not to alter its velocity but to change its internal structure – to create new particles.

It is easy to imagine the astonishment of the scientists when they discovered that the pattern of change in the number of deflected particles, depending on the scattering angle, was exactly the same as that found by E. Rutherford for alpha particles scattered by thin films of matter.

E. Rutherford, having observed alpha particles that were deflected by angles of up to 180 degrees from their original direction, immediately proposed the hypothesis of the atomic nucleus – that is, that within the atom there exists something comparable in mass to an alpha particle and capable of sharply changing its trajectory.

A similar conclusion, now concerning elementary particles, had to be drawn by modern physicists. Accelerated electrons and protons, when colliding with target protons, were transferring their energy to certain internal structural units within the proton itself.

In short, they returned to what they had once departed from. Only seven years ago, atomic nuclei and nucleons

seemed to be bodies of different orders of complexity. And now, under new energetic conditions, the once elementary particles themselves began to resemble nuclei filled with nucleons.

Theorists had long proposed the so-called composite models of fundamental elementary particles. The most interesting of these turned out to be the quark model. In this model, hadrons appeared as systems composed of a certain number of hypothetical particles – quarks – possessing fractional electric charge.

Atomic nuclei, which consist of nucleons, can serve as quite a realistic model of an elementary particle made up of quarks, while collisions of relativistic nuclei can imitate collisions of high-energy protons.

Experimenters found indisputable evidence that the nucleon is an extended composite object. Yet, in order to construct a theory that correctly describes the behaviour of hadrons at high energies – when their velocities are close to the speed of light – it was necessary to understand in detail their internal structure.

Relativistic nuclear physics – the scientific field that originated at the Joint Institute for Nuclear Research – provides a new approach to this problem and gives a material foundation to the already existing exchange of ideas between nuclear physics and the physics of elementary particles.

Accelerating nuclei to speeds approaching that of light

is an extraordinarily difficult task. One can easily imagine the keen interest with which leading scientists from socialist countries examined the greatly enlarged first images of the tracks of relativistic nuclei displayed at the 29th session of the Scientific Council of the Joint Institute for Nuclear Research (JINR).

These unique photographs were called by the scientists the “autographs” of the deuteron – the first composite nucleus accelerated in a synchrophasotron.

At present, Dubna physicists are observing not only the behaviour in matter of the simplest bound system – a proton and a neutron with an energy of 11 billion electron-volts – but also the nuclei of the chemical elements helium and carbon, whose nuclei are accelerated up to 60 billion electron-volts. Research in the field of relativistic nuclear physics, begun at the Laboratory of High Energies in 1970, has been taken up and is being actively developed by American physicists as well.

- Usually everyone enjoys watching the performances of imitators, but everyone also understands that even the most talented artist cannot replace the original. Surely, relativistic nuclei convey only an external – or rather internal – resemblance to particles, yet act according to their own nuclear laws.
- It is not worth speaking so categorically about this. It is known, for example, that the interactions of relativistic nuclei obey a new regularity of the world of

elementary particles – scale invariance.

The main knot of the most pressing problems in high-energy physics is now tied in the theoretical modelling of those processes in which, during the collision of two nucleons, a large number of new particles are produced.

Reactions of multiple production, as physicists call them, are the most interesting result of the interaction between nucleons with the highest energies. The study of these most complex processes of the microworld occupies most of the time of experimenters working with the largest accelerators. Time and again they have been convinced that these reactions, too, occur according to strict laws of conservation of charge, energy, and momentum, and that the foundation of physics remains unshaken.

But scientists are not satisfied with the role of mere observers of the wonders that nature sometimes presents when they bring into operation another super-powerful accelerator. Physicists themselves wish to predict these wonders. Yet they lack the tools of prediction – theories.

A contradiction thus arises. On the one hand, no theory can be created until the question of the internal structure of hadrons is resolved and the special regularities of the processes of multiple particle production are revealed; on the other hand, without a theory, it is impossible to understand the laws governing the interaction of two high-energy nucleons.

One way or another, the problem of multiple hadron formation in the processes of strong, electromagnetic, and weak interactions today occupies a central place in high-energy physics.

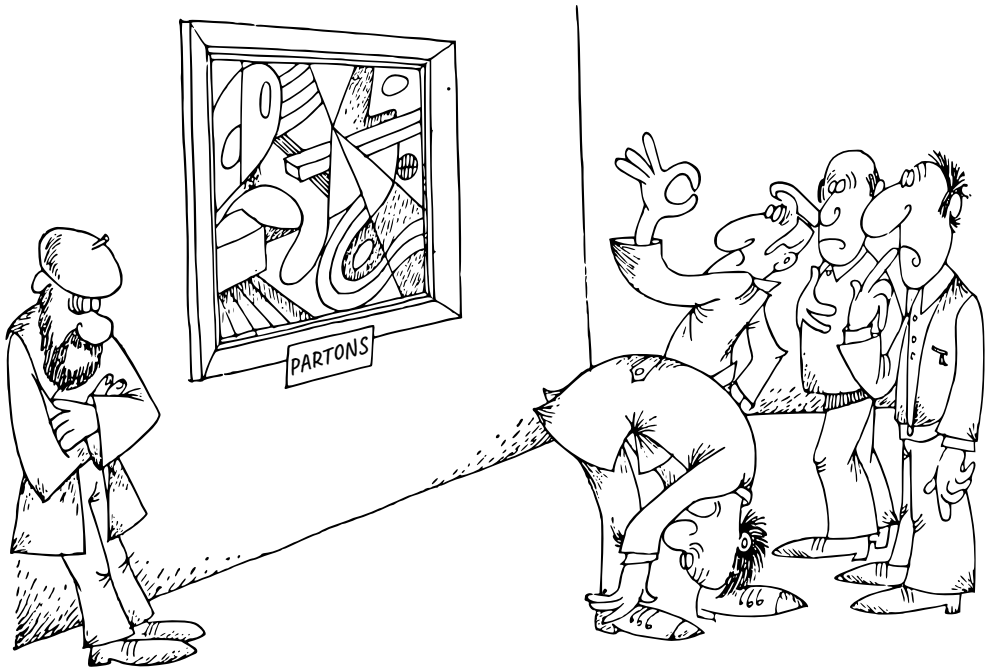
Despite the fact that intensive theoretical and experimental study of this question began relatively recently, the development of this most promising branch of physics has already given rise to new fundamental concepts, original approaches, and bold hypotheses.

Thirteen years ago, Academician M. Markov drew attention to the fact that in deeply inelastic scattering of electrons and neutrinos on protons – that is, in electromagnetic and weak interactions at high energies – the proton should behave as a point-like object.

Six years later, the American theorist J. Bjorken suggested that the probability of deeply inelastic scattering of electrons should possess the property of *scale invariance*, that is, depend not on the size of the proton or the masses of the colliding particles, but only on the ratio of their momenta.

Experiments conducted at the Stanford Electron Accelerator in 1969 confirmed this assumption. The unexpected feature of high-energy particle interactions led R. Feynman to the idea of the point-like structure of nucleons. In the model he proposed, hadrons contain an infinite multitude of elements of vanishingly small size, which were named partons.

The hypothesis of partons is now being vigorously discussed. True, as A. Baldin noted, instead of formulas, one usually draws pictures resembling abstract paintings. And often, the author of the next picture probably does not fully understand what he is drawing, while the listeners pretend to understand. There is nothing strange in this. On the forward front of the science of the microworld, where knowledge contends with absolute ignorance, truth crystallises only gradually.



It can now be said with certainty that nucleons consist of some more elementary entities. The entire problem lies in how to describe this actually existing complex structure of hadrons. It is possible that this can be achieved on the basis of the quark model. However, there is another approach to this problem.

A group of researchers from the Laboratory of Theoretical Physics at the Joint Institute for Nuclear Research, under the leadership of Professor A. Tavkhelidze, relying on the idea of the nucleon as a piece of special hadronic matter, succeeded in proving that the scale invariance – initially discovered in the electromagnetic interaction between the electron and the proton – should also manifest itself in deeply inelastic processes involving strong and weak interactions between particles.

Scale invariance is determined by the internal structure of elementary particles and is one of the most important manifestations of the properties of hadronic matter.

The dimensionlessness of those internal entities that absorb energy during deeply inelastic processes allows the interpretation of nuclear reactions both within the framework of the parton model and in the case where the proton is regarded as a continuous extended object.

Nature took pity on the physicists and simplified the laws governing the interactions of nuclear particles at high energies. Indeed, experiments carried out at accelerators in CERN, Serpukhov, and later in Batavia (USA), revealed a remarkable general property common to all processes of

multiple particle production. The complex mathematical formulas that physicists had previously used to describe various reactions between lower-energy protons suddenly became entirely unnecessary. In this new energy domain, the outcome of a collision between two particles depended only on the ratio of the momenta of the incoming and produced particles.

The unexpected uniformity of many processes – discovered by experimenters in catastrophic collisions between two particles over a wide energy range from 10 to 400 billion electron volts – resembles a journey through a desert without landmarks. Whether you ride on a camel or speed in a car, the information is reduced merely to the number of days and the length of the path travelled. The impressions are completely independent of whether you imagine the surrounding dunes as monolithic or as made up of countless grains of sand.

Scale invariance was discovered in that range of particle-interaction energies where the ratio of the squares of particle momenta is much greater than the squares of their masses. It is in this same energy region that relativistic nuclear physics studies the interactions of nuclei.

The formulation of the problem of applying scale invariance to relativistic nuclear collisions, as well as the first experiments in this area, were proposed and carried out at the Laboratory of High Energies of the Joint Institute for Nuclear Research (JINR). It turned out that the new regularity characteristic of hadronic matter at high energies

is also applicable to relativistic nuclei. In turn, the study of relativistic nuclear collisions will help to better understand the specific nature of multiple particle production processes.

In collisions between two nucleons, dozens of new particles are produced. The same happens in the collision of relativistic nuclei. Yet there is a fundamental difference between these seemingly similar events of the microworld – a difference that physicists have used to investigate the details of elementary particle interactions.

The structure of the two nuclear participants in the reaction is known, which cannot be said of nucleons. When nuclei of different chemical elements are accelerated, it becomes possible to vary widely the quantum properties of the colliding objects and to compare the features of collisions between light and heavy nuclei. In this way, it may become possible to find the most suitable model even for an elementary particle.

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– One might agree that the nucleus, with its nucleons, really resembles a composite elementary particle. But surely it cannot imitate a particle – a piece of continuous hadronic matter? – Why not? At very high energies, when the probability of processes depends neither on the size of the internal structures of the interacting objects nor on their mass, it is quite reasonable to assume that the nucleus is an archipelago of large islands of continuous hadronic matter. – One can assume anything. But, as one literary character said, science should not be speculative but empirical. – Quite right!

Recently, experimenters obtained confirmation of the validity of the new conception of the nucleus. Scientists at Dubna discovered a new physical phenomenon – the nuclear cumulative effect. It was discovered in 1971, soon after the Synchrophasotron of the Laboratory of High Energies first began accelerating deuterium nuclei (called deuterons) to an energy of 11 billion electron-volts.

When a deuteron collides with a proton, a lighter particle – a pi-meson – is produced. The essence of the cumulative behaviour of nuclear matter in this reaction lies in the fact that the pi-meson immediately acquires the combined energy of both the proton and the neutron. The two nucleons that make up the deuterium nucleus behave as a single particle.

This result was not merely new or unexpected; it com-

pelled physicists to abandon entirely the views they had formed over many years of studying non-relativistic deuterons.



Which of the possible interpretations of the internal structure of hadrons, consistent with the principle of scale invariance, was suitable for describing phenomena in relativistic nuclear physics?

According to the parton model, a nucleon behaves as a collection of point-like particles – partons – each of which

interacts with the target partons completely independently of the others. A relativistic nucleus could thus be imagined as being filled with a parton gas. This model (R. Feynman's model), when applied to complex nucleon systems, made it possible to base calculations on the principle of scale invariance.

However, the question of what maximum energy a nucleus could transfer to a particle produced in a reaction remained open. Something definite on this matter could be learned only if it were known with what probability the greater part of the internal energy of the nucleus would concentrate in one of the partons involved in the interaction with the target. But this very quantity could not be derived from the parton model of elementary particles.

The approach developed by Dubna theorists, which treats hadronic matter as a homogeneous, continuous medium, proved to be far more fruitful.

However, in all models of atomic nuclei without exception, the spatial extent of nucleons was never taken into account: they were simply regarded as point-like. And although the distances between protons and neutrons were comparable to the sizes of the particles themselves, such a crude simplification did not hinder the success of conceptual models of nuclei.

As the saying goes, "You cannot hide an awl in a sack." Likewise, relativistic nuclei can no longer conceal the fact that they essentially consist of extremely dense condensations of nucleon clusters, which behave like islands of con-

tinuous hadronic matter. The collision of a fast-moving nucleus with a proton appears as the impact of one of these islands, for which, as for an elementary particle, the relation of scale invariance must hold.

According to A. Baldin's hypothesis, a pi-meson produced in the interaction of a proton with the protons of a target nucleus inherits the combined energy of all the nucleons belonging to the group that included the direct participant in the reaction. The theoretical prediction was clear: experimenters should be able to detect secondary particles whose energies far exceeded those expected under ordinary kinematic laws.

Transforming the JINR synchrophasotron into a relativistic nuclear accelerator made it possible to test the idea that the energy of several nuclear particles could accumulate in a single one during the interaction of fast deuterons with protons.

To many physicists, the assumption of a cumulative effect seemed implausible. They argued that the deuteron, being such a loosely bound system, could not behave as a solid grain of hadronic matter. "Why, for example, when two stones collide, are high-energy elementary particles not produced?" – this was how the extreme scepticism toward the new point of view was often expressed.

But this question was not fatal for the hypothesis of the cumulative effect. It was unreasonable to expect that all the nucleons of the colliding stones' nuclei would transfer most of their energy to a single newly born particle. The

force of impact between any macroscopic bodies (such as stones) is far too weak, and the nuclei of those bodies do not even come into contact; the interaction is limited to collisions between the electronic shells of atoms.

In 1971, a group of experimental physicists from the Laboratory of High Energies at JINR, led by Doctor of Physical and Mathematical Sciences V. Stavinsky, discovered the cumulative effect in a reaction involving accelerated nuclei of heavy hydrogen isotope – deuterium. The pioneering results obtained by the Dubna scientists confirmed both the applicability of scale invariance to composite nucleon systems and the validity of the theoretical conception of the nucleus as a group of micro-islands of continuous hadronic matter.

The pi-mesons produced in interactions between relativistic deuterons and protons received up to 98 per cent of the total energy of the accelerated nuclei. But the deuterium nuclei are the simplest structures. Physicists now had to determine how more complex nuclear systems would behave. And where could they find relativistic heavy nuclei, when the accelerator could produce only deuterons? A hopeless situation?

Nothing of the sort. The scientists did not succumb to discouragement for long. With complete rigour from the standpoint of mechanics and with great ingenuity from a general point of view, they reasoned that if it was impossible to hurl relativistic nuclei at protons, one could instead hurl high-energy protons at stationary heavy target nuclei.

If one then recorded the pi-mesons emitted at an angle of 180 degrees to the beam of accelerated protons – that is, in the backward direction – the reaction would appear as the reverse one: a fast nucleus striking a proton. And if the cumulative effect truly existed, it could be detected by measuring the energy of the pi-mesons.

That is precisely what the experimenters did. Electronic instruments recorded that from the nuclei of carbon, aluminium, copper, and lead, pi-mesons were emitted with energies reaching up to 700 million electron-volts. Yet the maximum energy that pi-mesons could gain in an ordinary collision of two protons – so to speak, one on one – should not have exceeded 244 million electron-volts.

The scientists obtained the same result in the reaction of producing positively charged pi-mesons and also for heavy K-mesons.

The islands of hadronic matter within nuclei manifested themselves with the probability predicted by theory. Judging by the energy of the secondary particles, up to four nuclear nucleons sometimes participated simultaneously in a single collision.

Noting the significant contribution made by scientists from the Soviet Union and the countries of people's democracy to the work of the Sixth International Conference on High Energy Physics and Nuclear Structure, the well-known American physicist Professor G. Andersen remarked: "Many of the scientific reports at the conference have an Eastern accent."

Among these, without doubt, were the Dubna results obtained in the field of relativistic nuclear physics – a discipline connected with fundamentally new aspects of interactions within nuclear matter. The most engaging discussions arose precisely around the cumulative effect.

Not so long ago, some short-sighted specialists claimed that the era of exciting discoveries in nuclear physics had ended, leaving only the prosaic task of filling in details. Yet atomic nuclei continue to present one surprise after another. One such surprise – the cumulative effect – still awaits deeper understanding. This problem acquires special importance in connection with the idea of the quark structure of nuclear matter.

The deuteron – a weakly bound system of two particles – at relativistic speeds transforms into a compact, dense nucleus. Only when its two nucleons act together in a nuclear reaction do the emitted π -mesons acquire maximum energy. Yet, according to the quark model, each nucleon consists of three quarks. If a high-energy deuteron manages to compress its particles so tightly, it is possible that in some other high-energy reactions it will reveal its quark structure and behave not as a two-nucleon, but as a six-quark object.

Dubna physicists are now preparing experiments on the scattering of relativistic deuterons and helium nuclei to test this hypothesis. For the same purpose, American scientists studied the scattering of the highest-energy electrons on deuterium nuclei. The results of the experiment

suggest that, in this reaction, the deuteron indeed appears to behave as a six-quark particle.

- It seems that as the pressure on the atomic nucleus increases, it, like a chameleon in a moment of danger, changes its “appearance”. But when the “danger” passes, does the nucleus become itself again, or not?
- It depends on what you mean by “changes its appearance”! As a result of a reaction, the nucleus may lose one or several nucleons, break up into several parts, or pass into an excited state. However, in all these cases, the main property of nuclear matter – its density – does not change.
- Does it really not yield to any external influence?
- One cannot state this categorically. Just as graphite under high pressure turns into diamond, it may be possible to compress nuclear matter and transform it into an ultradense, stable state.

The Soviet theorist A. Migdal proposed one of the most intriguing modern hypotheses about the structure of the nucleus, in which he ventured to question the very property of nuclear matter that had so far remained unchanged.

While analysing the process of creation and condensation of electron-positron pairs near hypothetical nuclei with large electric charges, he arrived at an interesting idea: might it be possible to find in nature such a source of a mesonic field in whose presence the intense creation of pi-mesons would occur? Naturally, such a field could

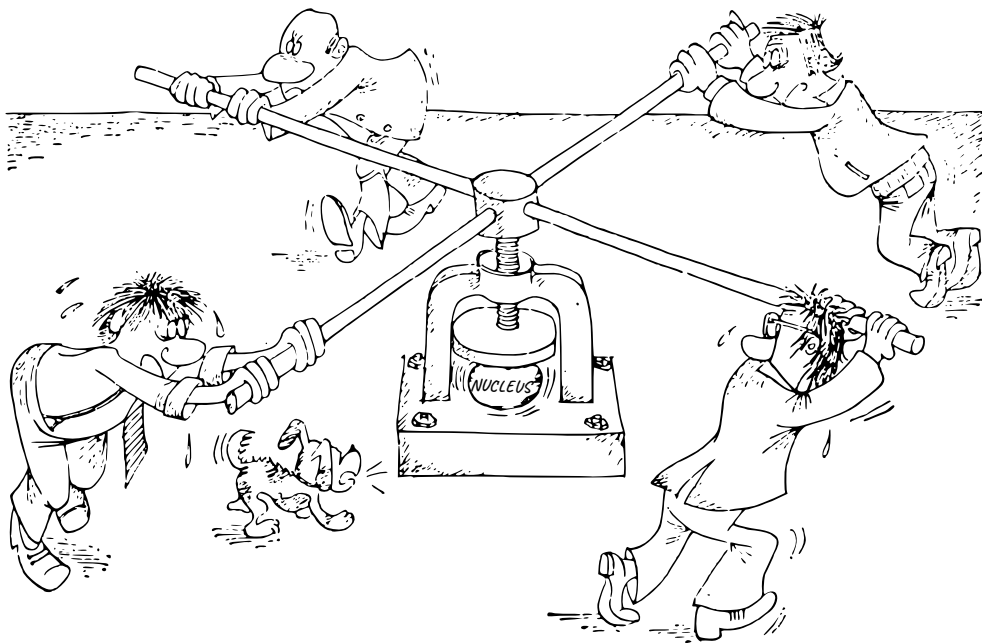
arise only somewhere within a large collective of bound nucleons.

Contemplating this problem led A. Migdal to an important conclusion: the creation and condensation of pi-mesons – that is, the formation of the so-called “pi-meson condensate” – could occur only in a system of protons and neutrons whose mechanical moments are oriented in a specific way.

Unfortunately, the modern theory of nuclear matter does not yet allow for sufficiently precise prediction of the exact nucleon density at which excess pi-mesons will begin to “separate out”. It can only be said that this density should not differ greatly from the ordinary nuclear density.

If the critical density turns out to be slightly lower than that of normal nuclei, then the condensate is an inherent property of ordinary nuclei, and the pi-meson condensate is associated with a layered nuclear structure. But if the appearance of the condensate occurs only in denser nuclear systems of nucleons, then it is clear that ordinary nuclei are not a suitable arena for the manifestation of the predicted property of nuclear matter. In that case, according to A. Migdal’s theory, nuclei may exist in special, superdense states.

It turns out that two only slightly different values of critical density correspond to entirely different states of nuclear matter.



As we already know, nuclear particles, owing to their constant motion, momentarily create within the nucleus regions that are either more rarefied or more dense. However, the average density of nuclear matter remains constant. So what must be done to the nucleus to test whether it can become superdense?

A realistic possibility for testing the compressibility of nuclear matter was suggested by particle physics – specifically, by the results of studies on multiple-production reac-

tions. Nucleons, hyperons, and mesons that arise simultaneously at a single point in space rush forward in a narrow, weakly diverging stream in the direction of the particle that created them. This feature of a nuclear catastrophe, as theorists explain, is associated with the instantaneous formation within the hadronic matter of a rapidly moving clump – a fireball – which, upon exiting the nucleus, disintegrates into numerous individual particles. The fireball generates a shock wave, and along its front, condensations of nuclear matter are formed.

A single fast proton, through the action of a shock wave, compels all the nucleons in a nucleus to engage in collective motion possessing very high energy. And the “ninth wave” that arises when two relativistic nuclei collide can increase the density of nucleons to such an extent that the nucleus transitions into a new quantum state – a superdense one.

Whether the nucleus in this new state will be stable or, on the contrary, unstable – remains unknown. In ordinary nuclei, the constant density is maintained by an equilibrium between attractive forces and the equally powerful repulsive forces that arise at small distances between nucleons. Yet it is possible that, at even closer separations of nuclear particles, they might begin to attract each other again. In that case, it would be natural to assume that at these ultra-short distances nuclear matter “collapses” into a more compact, more tightly bound system of nucleons.

The formation of a stable nucleus with increased den-

sity must be accompanied by the release of energy tens of times greater than, for example, that produced in the fission of a uranium nucleus. Therefore, the discovery of a superdense state of nuclear matter and the possibility of artificially producing superdense stable nuclei would bring about a genuine revolution in nuclear energy.

The first paper by A. Migdal, presenting in detail the foundations of the new hypothesis on the structure of the nucleus, was published in 1971, but it initially went largely unnoticed by experimental physicists. Some time was needed to overcome the “healthy conservatism” of the scientific community.

At the International Conference on High-Energy Physics and Nuclear Structure in Santa Fe, the report on the latest results obtained by a team from the Institute for Theoretical Physics of the USSR Academy of Sciences, led by A. Migdal, was received with great interest. In recent times, attention to this original and fairly well-developed idea of superdense nuclei has been fuelled by the rapid development of relativistic nuclear physics. There is now hope that, with the help of accelerated complex nuclei, it will be possible to obtain supercompressed nuclear matter.

Recently, the first experiments aimed at detecting shock waves in the interactions of relativistic nuclei were conducted in Berkeley, USA. However, American physicists were unable to reach a definite conclusion. The attempt made by scientists from the Federal Republic of Germany, however, seems to have been more successful. By study-

ing the parameters of secondary particle tracks in photographic emulsions that had been irradiated by a beam of relativistic helium nuclei at the Dubna synchrophasotron, the German physicists arrived at a clearer result: the collision of relativistic nuclei gives rise to a shock wave that travels through nuclear matter at a speed only three times less than that of light.

Experimental physicists from the California Institute of Technology took advantage of the fact that the Bevatron accelerator could produce argon nuclei moving at relativistic speeds, and they attempted to use them to create superdense nuclei. The idea of the experiment was as follows. The incoming argon nucleus could, roughly speaking, bore a hole through a heavy target nucleus made of the chemical element lead. The ejected column (or cylinder) of compressed nucleons, joining with the argon nucleus, could then form a superdense nucleus with a charge greater than that of the original argon nucleus.

American scientists did not detect any secondary fast nuclei with large charges in this reaction. However, this negative result did not discourage anyone – neither theorists nor the experimenters themselves. It might simply have been due to the insufficient energy of the argon nuclei, or perhaps it was necessary to use heavier relativistic nuclei. It is possible that superdense nuclei can only be obtained with special relativistic accelerators of atomic nuclei, which do not yet exist in any laboratory in the world but have already been given a name – *nuklotron*.

- Shouldn't nuclear physicists, like elementary particle physicists, look into space? Perhaps they could find superdense nuclei on the Sun or in some distant galaxy?
- Indeed, scientists are pondering where such superdense nuclei might be found. But as intergalactic routes are not yet open, relativistic nuclear physics is helping humankind to explore the near-Earth region of space.

Scientists still know very little about what exactly the remote youth of the universe was like, and even what is known comes mainly from mathematical calculations – extrapolations backward in time, into the past. All the easier, then, to ascribe to that not quite clear past the emergence of everything that still lacks a precise explanation.

This period was thought to mark the birth of antiparticles, mysterious quarks, and Dirac monopoles. And it was quite natural to suppose that if superdense nuclei exist in nature, they must have arisen during this early stage in the development of the universe, when its matter was still superhot and superdense.

The English theorist A. Bodmer calls such highly dense nuclei collapsed nuclei. Collapsed nuclei are those in which the particles have managed to overcome the forces of repulsion and 'collapse' into a lump roughly the size of the range of nuclear forces.

The subsequent fate of these superdense, primordial nuclei could have been different. According to Bodmer's hypothesis, they might have condensed together with their own kind to form very compact, massive black holes, or they might have dispersed into interstellar space. Finally, they could exist alongside ordinary matter. In that case, during the formation of planets and stars, as denser particles of matter, they would have settled in the central regions of massive bodies.

A. Bodmer suggests that if the cores of stars and planets contain a significant number of superdense nuclei, the reaction of these nuclei capturing ordinary ones could serve as an additional source of heat for cosmic bodies.

An original possibility — heating by “consuming” one's own nuclei! It is not impossible that the generation of colossal energy in quasars and galactic centres involves the effect of nuclear collapse.

Superdense nuclei might also have survived in the remnants of protostellar matter, which, according to Academician V. Ambartsumian, may still exist in the depths of space.

Studies of reactions involving collisions of particles with heavy relativistic nuclei, or of the nuclei themselves, may reveal how well-founded the theorists' hypotheses about the collapse of atomic nuclei actually are.

In head-on collisions of uranium nuclei with energies up to 2.5 thousand billion electron-volts, calculations show that the resulting shock wave compresses nuclear matter

to a density a hundred times greater than normal. In such a clump of highly heated nuclear matter, dozens of mesons and many hyperons are formed – producing something resembling protostellar matter.

If this imagined nuclear reaction were ever to be realised in the laboratory, the physics of the pre-stellar state of the universe would become an experimental science.

At present, it is impossible to say when experimenters will be able to test the cosmological aspect of the problem connected with such an unusual state of matter as the superdense one. Yet even now, relativistic nuclear physics is helping to solve certain questions that arise in the study of galactic cosmic radiation.

Searches for superheavy nuclei in cosmic rays have so far been unsuccessful, and physicists have not yet found a satisfactory explanation for this phenomenon.

Exploding supernovae appear, from time to time, to supply interstellar gas with the nuclei of heavy elements. According to current ideas about nucleosynthesis, the Earth's surface should occasionally be reached by superheavy galactic travellers. Nuclear astronomy – that is, the study of the cosmos through the detection of streams of complex, high-energy nuclei – could make a serious contribution to solving astrophysical problems. Yet so far, it has not been possible to establish contact even with our own Galaxy in this language. Why?

It is still not entirely clear what happens to the nuclei

of cosmic radiation from the moment of their birth until they reach the surface of the Earth. Interstellar gas and dust are extremely rarefied; cosmic space is practically empty. Yet streams of elementary particles and nuclei – messengers from distant stars – travel such enormous distances that even their rare encounters with cosmic dust particles significantly alter their original energy and mass.

On their way to Earth, heavy nuclei ‘lose weight’ through decay reactions, breaking into lighter fragments when colliding with other nuclei. After such “road accidents”, the flow of cosmic rays gradually becomes enriched with isotopes of lighter chemical elements, and scientists can only make various assumptions about the original composition of galactic radiation nuclei.

Relativistic nuclear physics makes it possible to model the collision processes of high-energy heavy nuclei of extraterrestrial origin. By measuring the probability of nuclear fragmentation and studying how energy is distributed among the resulting fragments, scientists may be able to reconstruct much more accurately the conditions under which heavy and superheavy nuclei are born and accelerated in the Galaxy.

Until humans ventured into outer space, the streams of elementary particles and nuclei forming there were of interest only from the standpoint of solving scientific problems unrelated to biology or medicine. Now a completely new aspect of the old problem of cosmic radiation has arisen. How does it affect a human being unprotected

by the thick layer of Earth's atmosphere? What radiation hazard is posed by fast nuclei of heavy elements?

It is well known that heavy multicharged particles differ from all other ionising radiations by the greater density of damage they produce along their path. How many such particles exist in open space?

The first experiments aimed at checking the degree of radiation hazard present in outer space were carried out in the 1950s with the help of balloons lifted to an altitude of 25 kilometres. Black mice were placed inside the instruments.

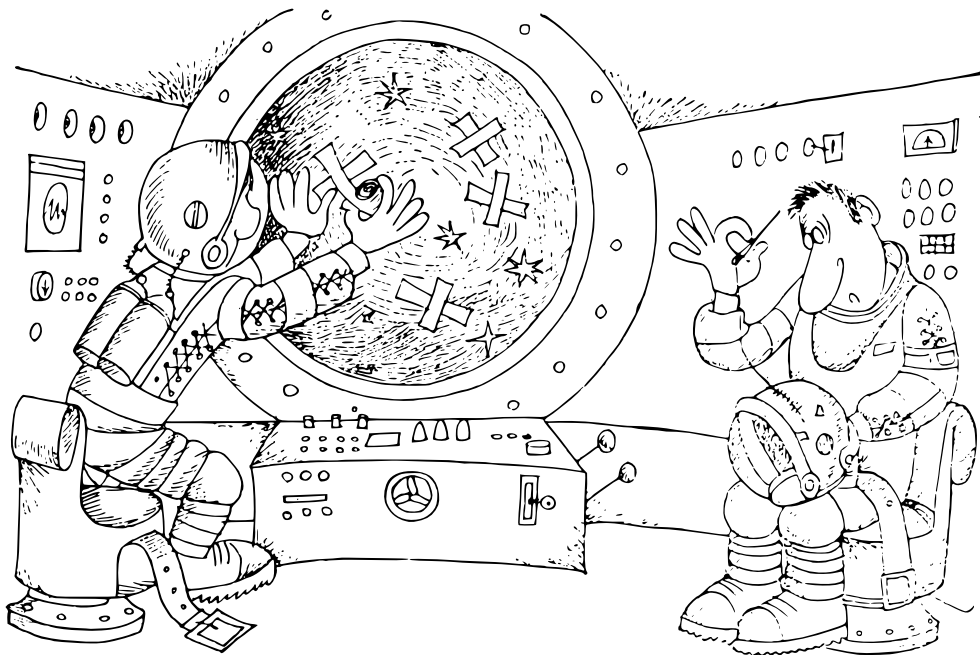
It is known that the pigmentation of each hair is maintained by only a few specialised cells that are highly sensitive to ionising radiation. Damage to these cells leads to discolouration of the hair – greying – which is very easy to observe. Stacks of nuclear emulsions were attached to the back of each animal. Upon returning to Earth, the emulsions were developed and examined under a microscope.

The scientists then compared the traces left in the emulsion by cosmic particles with the areas of greyed hairs. The results of these experiments, together with tests on animals conducted in particle accelerators, confirmed that fast nuclei from the stream of galactic particles destroy the pigment-producing cells. Remarkably, the impact of even a single heavy ion is sufficient to cause such damage.

During a series of space flights aboard the Apollo spacecraft, radiobiologists discovered the strong effects of relativistic cosmic nuclei on bacterial spores, plant seeds,

rootlets, seedlings, and crustacean eggs.

The most interesting discovery made by American astronauts was the so-called phenomenon of *phosphenes*. The participants of space flights periodically experienced flashes of light when their eyes adapted to darkness. This observation, made beyond the Earth, was later verified in the laboratory at the Bevatron (USA) using artificially accelerated heavy nitrogen nuclei. Phosphenes appeared at the moment when highly ionising particles destroyed the light-sensitive elements of the retina.

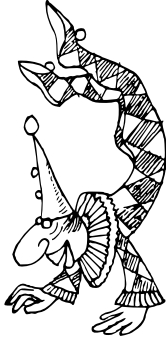


Apparently, the ultrafast heavy nuclei of cosmic radiation pose the greatest danger to nerve tissue cells, which lack the ability to regenerate. In the helmets of American astronauts who were aboard the Apollo spacecraft, traces of particles that had completely penetrated through them were found.

Based on the number of traces found, scientists have roughly estimated that during a space flight lasting one year, approximately one percent of the neurons in the human brain could die.

Experiments with artificially produced relativistic nuclei will help to determine precisely the degree of their danger to the human body and to develop reliable methods of protection.

"PURE" HEAT
OF
NUCLEAR
DEPTHS



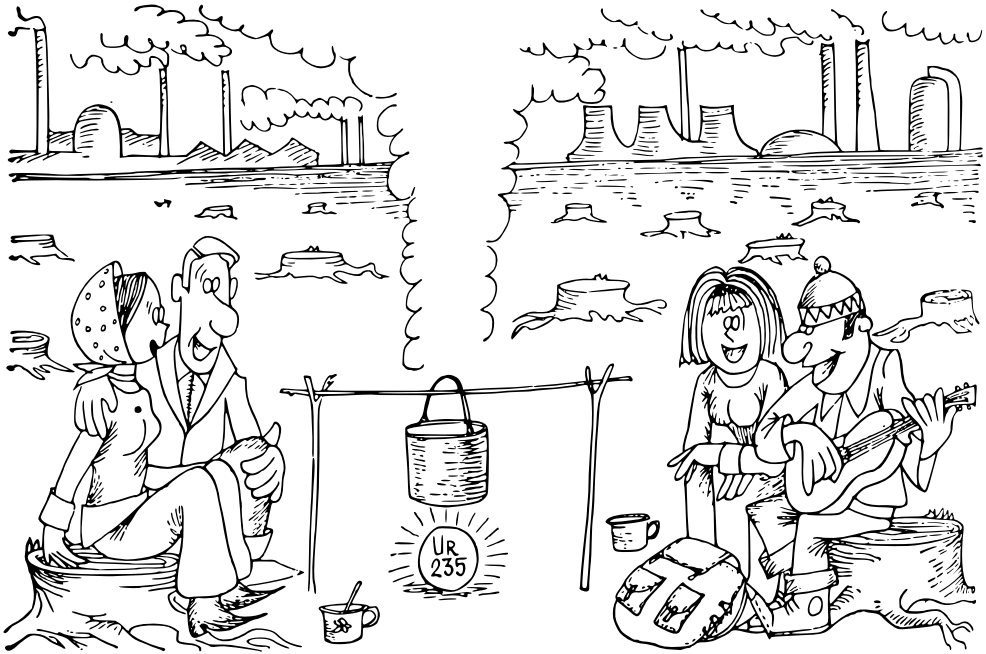
7 “Pure” Heat of Nuclear Depths

– Of course, the exploration of outer space is a very important task. But nuclear physics has probably not yet done everything possible on Earth? – You are right. The main problem for humanity is still not fully solved. The problem of providing future generations with practically inexhaustible sources of energy. And there is no time to waste. – You mean the energy crisis? – Not so much an energy crisis as an environmental one!

Modern civilisation has provided us with comfortable living conditions, but unfortunately, it has also instilled in people a careless attitude towards nature, the consequences of which we are beginning to feel. Nuclear physics has already proposed an ecologically cleaner source of energy than the reaction of chemical oxidation. This will help reduce the rate of pollution of the Earth's biosphere.

CHAPTER 7. "PURE" HEAT OF NUCLEAR DEPTHS

In the past, humanity obtained energy without caring how a particular method of extraction affected the surrounding environment. The growing capitalism demanded more and more energy and used whatever raw materials were readily available. And what was available were coal, oil, and gas.



The same valuable organic raw materials provide energy for us too, the generation of the late twentieth century. Only now, the absolute amount of energy consumed has

increased many times over, and consequently, so have the rates of burning combustible materials.

The poet A. Blok wrote at the beginning of our century: “... the world is green and blooming, and upon its breast lie the pot-bellied spiders – cities, sucking the surrounding vegetation, exhaling hum, smoke, and stench.”

The poet’s keen sense of unease, the deep concern of certain scientists for the future of civilisation, indicated that humanity – through the eyes of its most perceptive minds – did not suddenly but gradually realise that bit by bit “nature is turning into the environment.”

The nineteenth century bequeathed to the twentieth a still “blooming and green” world. What, then, will the twentieth century leave behind?

The modern poet L. Martynov already worries that

So that one day the Earth does not bake
into a single extinct volcano,
Not even erupting lava, –

and hopes that the coming generation

...Will once again return waters – to rivers,
blossoms – to flowers,
skies – to clouds...

The scientific and technological revolution, triumphantly sweeping through the developed nations of the world, has

set in motion such immense productive forces that humankind has gained almost unlimited power over nature. In a short time, it has turned from the "lord of nature" into its destroyer and a slave to its own needs.

The extraction of energy on an ever-increasing scale is one of the most serious factors working against humankind. At the beginning of the century, one could speak only of the emergence of local ecological crises (ecology being the science of the interaction between organisms and their environment), but today there are grave concerns regarding the relationship between human society and nature as a whole—that is, the possibility of a global ecological crisis.

When coal, oil, or gas is burned in the furnaces of thermal power stations, the concentration of carbon monoxide in the atmosphere continuously increases. The Earth, receiving its share of solar energy, radiates part of it into space in the form of infrared emission. A polluted atmosphere allows infrared photons to pass through much less efficiently. It covers our planet like a blanket, contributing to its overheating. Thus arises the so-called greenhouse, or hothouse, effect.

Corresponding member of the USSR Academy of Sciences, M. Budyko, demonstrated that this will occur if the average temperature on Earth rises by even one degree, or perhaps by half a degree. Such a seemingly small but universal increase in temperature may reduce the temperature gradient between equatorial and polar regions.

This levelling would immediately weaken the circulation of air masses between those latitudes, sharply reducing precipitation in the temperate zones and accelerating the spread of deserts.

All these changes could occur within a very short span—the lifetime of a single generation. Of course, this is a hypothesis, yet it is well-founded and may very well come true if humanity does not take the necessary measures.

One of the solutions is the widespread use of a fundamental discovery in physics—the chain reaction of uranium nucleus fission.

A decisive step in this direction was taken in the Soviet Union, where the foundations of peaceful nuclear energy were developed. The world's first nuclear power station, built in Obninsk, marked the beginning of a new era in energy technology. Today, nuclear power is developing at such a pace that, apparently, by the end of this century, more than 30 percent of all the electricity produced in the world will come from nuclear power plants.

But how long will the nuclear fuel last?

This perfectly reasonable question has long concerned both scientists directly engaged in solving nuclear energy problems and those working on fundamental research. Despite the large natural reserves of fissile elements, only a small fraction of them is used in nuclear reactors. This is due to the specific nature of the fission reaction of the uranium-235 isotope. Only its nuclei undergo fission when

struck by so-called "thermal" neutrons—that is, neutrons slowed down to speeds corresponding to the thermal motion of surrounding molecules.

The isotope uranium-238 requires neutrons with energies of about one million electron-volts to undergo fission. In a reactor where only uranium-238 is used as fuel, the neutrons emitted by fissioning nuclei are slowed down in the medium to several thousand electron-volts and lose the ability to induce fission in other uranium-238 nuclei, so the chain reaction dies out very quickly.

Thus, the isotope needed for nuclear power, uranium-235, is very scarce in nature – there will be barely enough of it until the beginning of the next century – whereas uranium-238 is, on the contrary, available in abundance, but it does not fission in a reactor. A deep study of the properties of atomic nuclei helped to find several fundamental solutions to the nuclear-fuel problem. By absorbing neutrons, uranium-238 nuclei, after a few radioactive decays, turn into nuclei of the isotope plutonium-239, which has the same fissionable properties as uranium-235. But where can we get so many neutrons to produce the required amount of nuclear fuel?

First of all, one should not lose the neutrons born in the reactor during fission of uranium-235 nuclei. The first installations so-called fast-neutron reactors have already been created; they perform two functions at once: they produce energy and convert "non-fissile" uranium-238 into fully fledged nuclear fuel. Thanks to the special design

of these reactors, that portion of the neutrons produced in fission of uranium-235 which does not participate in the chain reactions is captured by uranium-238.

But the problem as a whole is still not solved. It will take a great deal of effort by scientists and engineers to make the rate of nuclear-fuel production keep up with the pace of energy development.

Physicists engaged in studies of the fundamental properties of atomic nuclei, for their part, propose new methods of obtaining “fuel” nuclear materials. One of them – the electro-nuclear method – envisages joining a proton accelerator with a nuclear reactor into a single system. In it uranium-238 is converted into plutonium-239, which then releases energy when it fissions in the reactor.

Recently scientists have been considering yet another fundamental possibility for transforming uranium-238 into an isotope suitable for nuclear power – by means of... a neutron accelerator.

A method for accelerating neutral particles seems not to exist. All modern synchrotrons, cyclotrons, and synchrocyclotrons accelerate charged – and only charged – particles. In both the smallest and the largest of these devices particles are driven by an electric field. But what can you use to push a neutron?

The idea of accelerating neutrons was proposed in 1959 by the Soviet scientist Yu. Petrov. Of course, this hypothesis cannot be tested on any of the known types of accelerator.

The extra portions of energy must be given to the neutron by... nuclei that are in an excited state, that is, that possess excess energy.

Imagine that it was possible to create a special medium in which a significant fraction of the nuclei are not in the ground state but in an isomeric one. This medium resembles the working substance of a gamma-laser, saturated with isomeric nuclei (as discussed in the previous chapter). A neutron, colliding with a nucleus, as it were releases the cock of the nuclear trigger. The system of bound nucleons transitions to the ground state, and the neutron takes away its excess energy.

In this unusual accelerator the neutrons, gaining energy in chaotic collisions with excited nuclei, resemble bees bustling around flowers in search of nectar. Far from every flower contains a sweet drop, and far from every encounter of a nucleus with a neutron leads to an increase of the neutron's energy. The nucleus may turn out to be unexcited.

In that case the neutron not only fails to increase its energy but can lose energy it had previously accumulated, if the mass of the nucleus only slightly exceeds its own mass. An isomeric nucleus, shedding its excess energy in a collision with a neutron, experiences recoil. More massive isomeric nuclei are preferable in a neutron accelerator, since they expend far less energy on recoil than light ones.

In a neutron accelerator, there must not be isomeric nuclei that possess reserve excitation levels at energies

equal to those to which one intends to accelerate the neutrons. Otherwise, instead of being accelerated, the neutrons themselves would begin to “pump” energy into the nuclei, transferring them into excited states.

Preliminary theoretical estimates indicate that a suitable isomeric medium could serve as an accelerator for neutrons up to energies of one or two million electron volts.

In an installation containing uranium-238 mixed with isomeric nuclei, a self-sustaining fission reaction might apparently arise.

Indeed, the excited nuclei, by transferring their energy to the neutrons, would keep them in excellent “athletic” condition, and they would constantly remain capable of overcoming the high energy barrier of uranium-238 fission.

Scientists are still discussing only the fundamental questions related to the creation of such an isomeric reactor. Yet, an unexpected and radical idea could immediately advance the solution to this problem.

Not long ago, a group of Soviet scientists proposed using a laser light beam to compress fissile material, increasing its density hundreds of times. Naturally, if successful, this would immediately reduce the critical amount of material required for a self-sustaining nuclear fission chain reaction.

This idea might bring closer the moment of testing the

hypothesis of an isomeric reactor. It would help to bypass the main difficulty in its practical realisation—the need to prepare a huge quantity of isomeric nuclei.

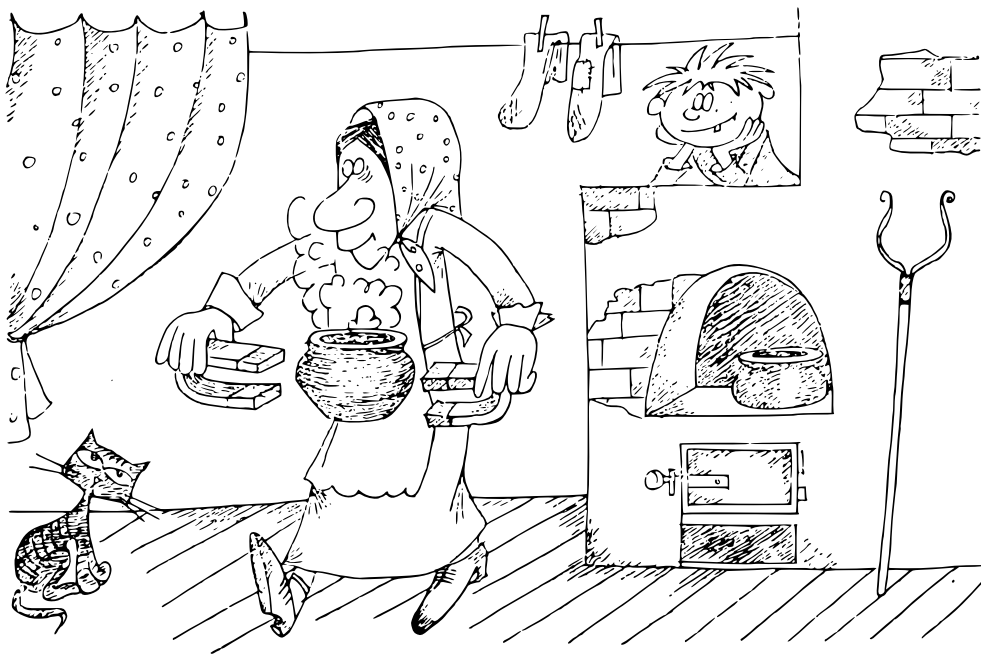
Once a reactor based on compressed fissile material is built, it will be possible to experimentally test the operating principle of the isomeric reactor, for which only a few grams of isomeric nuclei would be needed.

- And what will people do later, when the reserves of heavy elements are exhausted?
- With this in mind, physicists have long been trying to realise the second way of obtaining nuclear energy – by combining two light nuclei.
- Will the Sun's "experiment" not help us here?

In general terms, scientists know how the Sun's "installation" works – the one that produces the energy thanks to which life arose on Earth and humankind appeared. The fusion of hydrogen nuclei is the main nuclear reaction taking place both in distant stars and in our Sun. Physicists first reproduced this stellar reaction under terrestrial conditions back in 1932, immediately after the launch of the first accelerator.

Artificially accelerated nuclei of the hydrogen isotope – deuterium – collided with stationary deuterons (deuterium nuclei) in a target, turning into helium nuclei with a large mass defect. Each such event was invariably accompanied by the release of energy, in precise accordance with

A. Einstein's formula $E = mc^2$.



Two deuterium nuclei can fuse with each other only if they possess a speed sufficient to overcome the electrostatic barrier. Then, with a good run-up, they “vault” over this barrier and firmly bind together by the “protrusions” of nuclear forces.

Accelerating deuterons in an accelerator to the required energy and firing them at a target is not difficult. But only those particles that undergo a head-on collision will fuse,

which happens quite rarely; the rest, scattering on the cold atoms of the target, quickly spend their energy ionizing those atoms and completely lose any chance of ever coming close to each other. The target simply absorbs the energy of the incoming hot deuterons, returning only a negligible fraction of it in the rare reactions that synthesize two nuclei. Such sporadically flashing matches cannot kindle a nuclear "fire" in a cold target.

The fusion reaction of the nuclei of the heavy isotopes of hydrogen, like other isolated exothermic nuclear reactions, was never seriously considered a practical method for power generation. It yielded no net gain. So how is it that in stars this fusion reaction becomes energetically advantageous?

If the fourth dimension is a convenient mathematical abstraction, the fourth state of matter is absolute reality. The ancients called it fire; we prefer the word "plasma." Plasma is an ionized gas – that is, a mixture of charged nuclei and electrons.

ChatGPT said:

Almost all matter in the universe exists in this fourth state: both the Sun and the stars are made of incandescent plasma. In it, fusion reactions become sufficiently intense because many nuclei of hydrogen isotopes already possess enough energy to combine.

In the chaos of thermal motion, nuclei continuously collide with one another, but they no longer lose energy.

Therefore, even an unsuccessful, non-head-on collision does not remove a deuteron from play. If each nucleus undergoes several dozen collisions, one of them is almost certain to result in a fusion reaction. Such reactions are called thermonuclear because they occur in matter heated to very high temperatures.

The first experimental thermonuclear explosion, carried out in 1952, proved the possibility of releasing a vast amount of thermonuclear energy. But humanity is interested in creating a device that can extract thermonuclear energy not through an explosion but under strict control.

By analogy with nuclear reactors, where fission reactions of uranium nuclei proceed under human control, future devices for intensive but controlled fusion of light nuclei were named *thermonuclear* reactors.

The path from the discovery of uranium fission chain reactions to the creation of the first reactor was remarkably swift, but the road leading to the construction of a thermonuclear reactor has proven far more difficult, thorny, and exhausting.

Plasma has long served humankind. Not a single gas-discharge device functions without it. Every evening, fluorescent lamps and neon signs light up our streets, glowing with so-called cold plasma, whose ion temperature is close to room temperature. But to what temperature must deuterium plasma be heated for intensive fusion reactions to begin?

The thermonuclear reactor of the Sun operates at a temperature of about 15 million degrees. Yet this temperature is far too low for the plasma of a future energy-producing terrestrial reactor. And here is why.

The electrostatic barrier surrounding a charged deuterium nucleus has a height of about 400–500 kiloelectron-volts. But a temperature of 15 million degrees gives nuclei an average energy of only about 2 kiloelectron-volts. Most nuclei therefore mill about uselessly near one another, and only a few – those that happen to possess greater energy – enter into fusion reactions.

However, the Sun's reactor contains such an enormous mass of matter that even with the low probability of thermonuclear reactions in a not-so-hot plasma, a sufficiently large number of nuclei participate in the fusion process.

It is impossible to realize this under Earthly conditions. On a large scale one can obtain thermonuclear energy using the explosion of a hydrogen bomb, but one cannot use an explosion as a source of energy for peaceful purposes! The problem of harnessing thermonuclear energy is to extract it in small portions suitable for use in power engineering and transportation.

Thus, with a small amount of reacting material, all hope rests solely on temperature. Only by increasing the plasma temperature can one increase the probability of thermonuclear reactions. In a plasma heated to 100 million degrees, nuclei will on average have an energy of about 15 kiloelectron-volts – still many times less than that required

to overcome the electrostatic repulsion. Yet such a high temperature does make it possible for a substantially larger number of particles to enter into fusion reactions.

The energy that must be “pumped” into the plasma to ignite intensive thermonuclear reactions in it is relatively small. But just as a leaky bicycle tire quickly loses air, so the plasma rapidly loses the energy it has gained when it touches the cold walls of the vessel. Here even Prometheus would throw up his hands. He simply would have nothing with which to bring humanity the fire of a thermonuclear hearth.

In stars, enormous gravitational forces confine the hot plasma in the central region and prevent it from spreading out and mixing with the cooler layers. On Earth, physicists had to create such stellar plasma in the laboratory and learn to hold it in a heated state for some time.

“The problem of controlled thermonuclear fusion, in its difficulty, leaves behind all other scientific and technical problems spawned by the successes of natural science in the twentieth century,” — said Academician L. Artsimovich.

The idea that hot plasma can be held in the “hands” by means of a magnetic field arose roughly a quarter of a century ago. Plasma is produced by sufficiently strong heating of a gas. Already at a temperature of several thousand degrees the electromagnetic ties that keep electrons bound to nuclei begin to “break,” and at temperatures of millions of degrees practically all atoms fall apart into their constituent parts. Any even very small piece of plasma

remains electrically neutral, but it is not neutral atoms that move chaotically in it, rather equal numbers of positively charged nuclei and negatively charged electrons. Both kinds of particles obey a magnetic field, and therefore it seemed that plasma could be easily controlled by it.

At first, the idea of magnetic thermal insulation of plasma was realised in an ordinary discharge tube—the very instrument in which J.J. Thomson discovered electrons torn from atoms as a result of ionisation, and where, at the end of the last century, physicists first obtained matter in its fourth state. Through deuterium gas contained in the tube, a powerful electric discharge was passed for a millionth of a second. The current, heating the gas, created plasma, and the magnetic field of the current lifted it away from the walls and drew it towards the tube's axis. Now the plasma no longer touched the cold walls, and it could be heated to a million degrees. Thus, for the first time in the laboratory, scientists obtained matter at a temperature equal to that of the Sun's corona.

Did thermonuclear fusion reactions occur under such heating?

The main sign of the onset of thermonuclear fusion is the appearance of neutrons. Both in the formation of helium nuclei from two fused deuterons and in the reaction of a deuteron with the nucleus of the heaviest hydrogen isotope—tritium—neutrons are inevitably produced. Experimenters eagerly awaited the appearance of these neutrons in the hot plasma.

And so, on 4 July 1952, during one of a series of experiments at the I. Kurchatov Institute of Atomic Energy, the previously inactive neutron counters suddenly began to register activity. It seemed that the cherished goal—the achievement of a controlled thermonuclear reaction—was near. Yet the scientists were in for a bitter disappointment.

A detailed critical analysis carried out by the head of the controlled thermonuclear fusion research, Academician L. Artsimovich, showed that the detected neutrons were not of thermonuclear origin. The majority of deuterons did not have enough time to heat up to the temperature required for thermonuclear fusion reactions—the plasma was extinguished slightly earlier. What was the reason?

The explanation proved to be complex and intricate.

Plasma is a union of light electrons and heavy atomic nuclei bound by electric forces. As soon as it arises in the discharge tube, all its particles together act to expel the magnetic field of the current from its volume. The expelled field, in turn, presses strongly on the plasma's surface, shaping it into a plasma filament. This plasma filament does not touch the walls and, in theory, could exist for quite some time at a high temperature.

But plasma compressed by a magnetic field is extremely unstable. Even the slightest bend in the plasma filament causes the magnetic pressure at the bend to increase further, intensifying the distortion. The filament loses its shape, and the incandescent particles scatter against the walls of the tube.

In this very first attempt to control matter in its fourth state, scientists encountered its treacherous nature and met with failure. It became clear that an answer to the question, 'Is it possible to achieve a controlled thermonuclear reaction?' could be obtained only through the study of plasma itself.

Thus emerged a new science – high-temperature plasma physics – about which L. Artsimovich once half-jokingly remarked that it should not be counted among the natural sciences, since the natural sciences study objects created by nature, whereas plasma physics studies objects created by experimenters.

Today, more than a hundred magnetic "bottles" – various types of plasma traps – are operating in laboratories around the world. Some of them, such as the American Scylla, resemble a discharge tube in which plasma is confined by an auxiliary current-carrying conductor. However, in such a device, hot plasma exists for only a few millionths of a second.

In others, such as the Soviet system with magnetic plugs called Ogra, prepared plasma is injected into a tube in which the magnetic field at the ends is stronger than in the centre. Charged particles, like light reflected from a mirror, are repelled from regions of strong magnetic field, causing the plasma to oscillate between the magnetic plugs.

In the early 1960s, M. Ioffe, a researcher at the Plasma Studies Department of the Institute of Atomic Energy, succeeded for the first time in extending the lifetime of plasma

to tenths of a second. He arranged additional external current-carrying conductors so skilfully that the plasma could no longer leak between magnetic field lines and perish prematurely. This was a major achievement. Unfortunately, only very rarefied plasma could survive in such a device.

Physicists, however, know precisely what kind of plasma is required to reach the goal of economically viable thermonuclear reactions. Plasma consisting of a mixture of deuterium and tritium, heated to about a hundred million degrees, must have a particle density n (per cubic centimetre) and a lifetime τ (in seconds) such that their product $n \times \tau$ exceeds 3×10^{14} .

So far, no plasma device built in any laboratory in the world has achieved plasma with these required parameters. More often than not, one type of apparatus could heat plasma to very high temperatures, while another type achieved sufficiently long confinement times—but not both simultaneously.

Physicists had to solve an extremely difficult problem – to combine these record achievements within a single thermonuclear reactor.

- So, they needed to design some special magnetic home for the plasma?
- Yes, that is precisely what the physicists aimed for. And then a fortunate idea occurred to them – to con-

fine the plasma within a ring-shaped magnetic field.

- Of course, an excellent idea. As the saying goes, "a ring has no end", so the plasma would find no way out of it.
- It can still "find a way out" anywhere, even where none seems to exist. But the scientists gradually managed to "grow" in such a trap a plasma with the best possible characteristics.

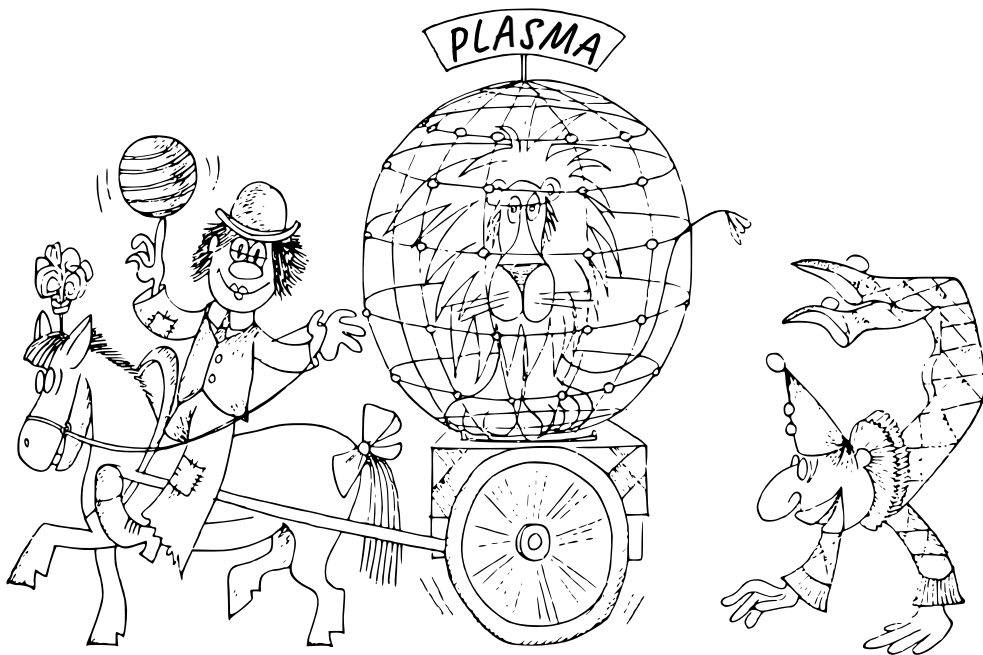
More than twenty years ago, under the direction of Academician L. Artsimovich, research began at the I. Kurchatov Institute of Atomic Energy on plasma devices of a closed type. In these devices there are no electrodes, and the plasma, as it were, closes upon itself.

These thermonuclear installations – now widely known – form the famous family of Tokamaks. The name Tokamak was created from the words denoting the main elements of the device: tok (current), kamera (chamber), magnitnye katushki (magnetic coils) – *to-ka-ma-k*. Until recently, the largest of them was Tokamak-4, which produced and maintained the best plasma in the world. The Tokamak does not strike the plasma with an instantaneous electric discharge of enormous power, nor does it drive it back and forth between magnetic plugs. Instead, the plasma flows freely within a torus-shaped chamber, following the lines of magnetic force.

The metallic toroidal chamber, filled with gaseous deuterium, is placed around an iron core. In this arrangement,

it acts as the secondary winding of a transformer. The current induced within the chamber heats the gas and turns it into plasma.

The plasma, held away from the chamber walls by the magnetic field that compresses it, manages to balance this magnetic pressure with its own gas pressure. Thus, it forms a ring along the axis of the chamber. But the question remains – how long can this ring survive?



Everything depends on how stable the plasma cord is, resting on the magnetic field lines. Imagine a ring made of very soft rubber, suspended horizontally on threads. It becomes deformed: where the threads are attached, constrictions appear, and in the spaces between them the ring sags.

The plasma cord is a tenuous cloud of ionised gas weighing only a few dozen micrograms. The toroidal chamber of the Tokamak is nothing but a vacuum chamber. The gas that would fill it at atmospheric pressure would weigh millions of times more. One can thus imagine how easily this delicate plasma cloud can be deformed by the magnetic field that confines it.

Unlike the stable deformation of a rubber ring, any deformation of the plasma, once it appears, inevitably grows: the cord loses its shape, and the plasma perishes against the chamber walls.

If one inserts a resilient steel wire into the soft rubber ring, it becomes stiffer. The role of such a resilient wire in the Tokamak's plasma cord is played by the lines of force of the longitudinal magnetic field, produced by an additional coil wound directly around the chamber. The closed lines of this field form circles parallel to the plasma cord.

These lines of force create the magnetic 'home' in which physicists confine the hot plasma: it is deprived of the freedom that had earlier led to its destruction.

The longitudinal magnetic field acts upon the particles

so that each begins to circle around its line of force and can move freely only along it. Motion across the chamber is forbidden by the laws of electrodynamics. Any portion of plasma that violates this restriction drags along the lines of the longitudinal magnetic field, which, owing to the collective properties of plasma, seem to be attached to it. As the elastic field lines straighten out, they restrain the intruding portion, and the growth of deformation ceases.

The rate of energy loss of plasma in the Soviet Tokamak installation turned out to be 50–60 times lower than that predicted by the American scientist D. Bohm.

In 1968, at a conference in Novosibirsk, L. Artsimovich declared: “We have freed ourselves from the grim spectre of enormous losses embodied in Bohm’s formula, and we have opened the way to further increases in temperature...”

This was a significant victory for the Soviet school of plasma physics. It took ten years of painstaking work and the joint efforts of experimentalists and the theoretical group led by Academician M. Leontovich for the plasma truly to feel “at home” in the Tokamak.

Surrounded by a double magnetic mesh, the plasma still attempted to slip through it. For individual charged particles, the combination of magnetic fields in the Tokamak forms an ideal magnetic trap. Yet, for the collective of plasma particles, this is far from the case. Even the shape of the chamber worked to the plasma’s advantage.

In a toroidal chamber, the plasma behaves as a con-

ducting loop carrying a current. And every self-respecting loop, when placed in a magnetic field, tends to stretch out like a coiled steel spring. As it unfolds, the plasma cord may touch the chamber walls and perish.

Fortunately, the Tokamak automatically handles this problem. The current flowing through the plasma surrounds it with a magnetic "blanket". It is this magnetic layer that reaches the walls before the plasma does. The lines of force, as they cross the thick metal wall of the chamber, induce in it an opposing current – the so-called *Foucault current* – directed opposite to the plasma current. And opposite currents always repel each other. Thus, instead of coming into contact with the wall, the plasma loop recoils from it.

For a long time, physicists carefully nurtured the plasma in the Tokamak. Year after year, they increasingly suppressed the 'microbes' of instability that shortened the hot plasma's life. Their persistent struggle against its ailments and weaknesses led to a great success – a nearly stable plasma was eventually cultivated within the Tokamak.

Yet, even when seemingly in a steady, balanced state, hot plasma still lives only briefly, being subject to all manner of random disturbances. One might say it is far more sensitive than the princess in the fairy tale – the one who felt a pea beneath many mattresses. Beneath a magnetic 'quilt' of forty thousand oersteds, the plasma can sense even a faint additional field of ten oersteds appearing nearby. The result is unfortunate: once disturbed, the plasma falls

out of equilibrium and strikes the chamber walls.

Another problem lies in the fact that plasma inevitably loses the energy it has gained. Between the plasma and the chamber walls there exists an enormous temperature difference. Although the chamber itself is hot, to the plasma heated to millions of degrees it feels icy cold. In obedience to the law of heat conduction, the hot plasma particles continually strive to transfer energy to the cold walls. Charged electrons and deuterium nuclei, while rotating around the lines of the longitudinal magnetic field, collide with one another and, as a result, hop from one line of force to another. In this almost imperceptible way, the particles reach the walls and transfer to them a significant portion of the plasma's energy.

The plasma living within the Tokamak places extremely high demands upon its home. It must be absolutely clean. Therefore, before each experiment, the chamber is meticulously purified: the air is pumped out for a long time at a high temperature. Yet even a few stray atoms of heavy elements clinging to the walls can detach and greatly cool the plasma. Each such atom carries a whole bundle of electronic 'clothing', and as the plasma strips these layers away – ionising the atom – it loses energy again.

The quality of the cultivated plasma can be judged only after the temperature of its ions and electrons and the density of its particles are known. Measuring these quantities in a substance existing in the fourth state of matter is exceedingly difficult. How does one approach plasma –

delicately swaddled in two magnetic fields, suspended in a deep vacuum, and hidden from the experimenters within a chamber of double metal walls? It is always nearby, yet it seems to exist in another world.

Nevertheless, scientists found methods to determine the number of particles in the chamber and to measure their temperature. It turned out that the ion temperature in Tokamak-3 reached 400 electronvolts (that is, almost five million degrees), and that of the electrons – 1000 electronvolts. (These results were confirmed in a joint experiment by British and Soviet physicists, in which the electron temperature and concentration were simultaneously measured in the Tokamak using lasers.) At such temperatures, some deuterium nuclei already possessed enough energy to engage in thermonuclear fusion reactions.

At the Tokamak-3 facility, scientists for the first time recorded sustained thermonuclear neutron emission from a stable plasma loop. In a device created by human hands, a genuine thermonuclear flame had flickered to life. Plasma of such quality had never before been obtained in any other closed-type plasma installation.

Working with plasma is much like the patient craft of a master carver working on stone lacework. Day after day, the skilled sculptor adds finer and finer details; day after day, scientists continue to improve the parameters of plasma.

Research on Tokamaks began with plasma temperatures of about 100,000 degrees and with the main plasma

parameter – $n\tau$ (the product of plasma density and confinement time) – around 10^7 . By the late 1960s, scientists had managed to raise the temperature to 5 million degrees and to increase $n\tau$ by a factor of 10,000.

At the Third International Conference on the Peaceful Uses of Atomic Energy, L. Artsimovich reported on the results achieved on Tokamak-3. His presentation aroused tremendous interest in the scientific community. Unexpectedly for many, Tokamaks had surpassed all other plasma devices and emerged as the most promising.

In June 1969, the United States Atomic Energy Commission approved plans to construct Tokamak-type plasma installations at laboratories in Oak Ridge and Princeton. Today, more than 30 large Tokamaks are either operating or under construction in laboratories around the world – eight in the Soviet Union, and others in the United States, the United Kingdom, France, Italy, West Germany, Australia, Japan, and China.

But the goal that still lies ahead of scientists can be considered achieved only when the first industrial thermonuclear reactor begins to operate.

Whether the conclusions drawn from experiments on present-day Tokamaks – which so far operate only at the physical thermonuclear level (that is, the reaction occurs without yielding a net gain in energy) – will remain valid for full-scale fusion reactors, remains an open question. This uncertainty troubles physicists working with hot plasma, and it can be resolved only through careful investigation

of plasma in new, more powerful installations. One such facility, Tokamak-10, has recently been launched in the Soviet Union.

The head of the Soviet thermonuclear programme, Academician E. Velikhov, stated:

"We must learn to heat plasma to 100 million degrees (so far we have reached the ten-million mark). Another condition is that the plasma density must be no less than 100 trillion particles per cubic centimetre – that is, twice as high as what we currently obtain. And most importantly, the plasma confinement time: in Tokamak-10 it is 0.01–0.02 seconds, whereas a full-scale thermonuclear reaction requires one full second."

The plasma density in Tokamak-10 will be the same as that expected in a future power-producing reactor. However, the key parameter $n\tau$ will reach only about 10^{13} , which is 10 to 30 times lower than what is required for an energy-producing reactor.

Soviet scientists have designed the first demonstration reactor with a large toroidal chamber five metres in diameter, named Tokamak-20. This device is likely to be the final laboratory prototype of an industrial thermonuclear reactor. In it, the plasma will be heated to between 70 and 100 million degrees.

The parameters and operational mode of this installation will already make it possible to obtain as much energy from the thermonuclear reaction as is spent on heating and confining the plasma.

With the help of Tokamak-20, scientists plan to address several crucial physical and technical problems – for instance, determining whether a sudden degradation of plasma thermal insulation occurs near 100 million degrees, and developing new, more efficient methods of plasma heating.

With the Tokamak-20 it will be necessary to solve very important physical and technical problems. For example, it is necessary to find out whether the thermal insulation of the plasma will sharply deteriorate at a temperature of about 100 million degrees; it is necessary to find new, more efficient methods of heating the plasma. If all these difficult tasks can be solved, then an energy-producing thermonuclear reactor – a power plant – can be built on the Tokamak principle.

- If it is so difficult to confine a rarefied plasma for a long time, couldn't one quickly burn the thermonuclear fuel, as happens in the explosion of a hydrogen bomb?
- In that case the installation might be destroyed. Scientists have found a more peaceful path: they tried to “detonate” small portions of nuclear fuel using a powerful flash of coherent laser light.”

There is no doubt that the “era of synthesis” will replace the “era of fission” once scientists succeed in achieving controlled thermonuclear fusion. Over the past ten years, a new direction has emerged and taken shape – one followed

by scientists attempting to "tame" the thermonuclear fire. Soon after the creation of optical lasers, which made it possible to concentrate enormous energy in a small region of space, the idea arose of rapidly igniting a thermonuclear fusion reaction using short pulses of laser light.

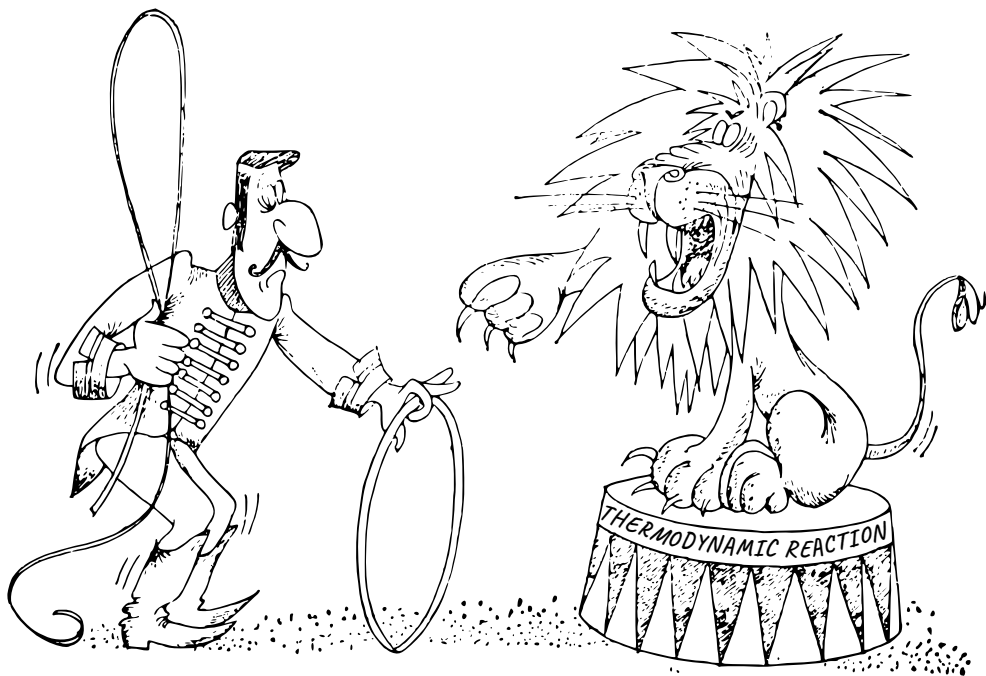
This approach, in principle, leads to the creation of thermonuclear reactors operating in a pulsed mode. While in Tokamaks – continuous-operation devices – scientists strive to increase the lifetime of the plasma, those working in the second direction face entirely different challenges.

In a pulsed thermonuclear system, energy is extracted from each portion of plasma so quickly that there is no need to struggle with its instability. Laser physicists agree with Oscar Wilde, who said that "the best way to get rid of temptation is to yield to it." They do not waste time trying to tame the plasma or alter its nature.

However, plasma left to itself lives for only a brief instant – during which its temperature must be raised to 100 million degrees. This is the first difficulty.

Secondly, it is necessary somehow to maintain the plasma parameter $n\tau$ at the required level, since τ (the confinement time) decreases catastrophically to about 10^{-9} seconds.

Having yielded to temptation – by giving plasma complete freedom – physicists have been forced to compensate by increasing as much as possible the second factor in the key plasma quality parameter: the *density*.



The amount of thermonuclear energy released at $n\tau = 10^{14}$ would equal the energy spent on heating the plasma. An energy gain of at least tenfold could be achieved if the number of particles in the plasma were increased ten times more.

A simple arithmetic calculation showed that physicists would have to ignite thermonuclear fusion reactions almost instantly in a substance with the density of a solid, which is about 10^{22} particles per cubic centimetre.

Without hesitation, scientists set out to create in the laboratory a plasma as dense as the Sun's core—but with a temperature ten times higher. But how could this be done? A plasma with the density of a solid could be produced in only one way: by heating a small piece of solid matter. Therefore, the target at which the researchers directed the laser beam was a kind of pellet made of a frozen mixture of deuterium and tritium.

A short pulse of laser light rapidly converted the thin surface layer of the substance into plasma and heated it to a high temperature. The plasma clump could not withstand the enormous pressure that arose within it due to the extreme temperature and density, and it exploded. A small thermonuclear explosion occurred.

Physicists note that if installations with long plasma confinement in a magnetic field resemble a steam engine, then a pulsed thermonuclear system is akin to an internal combustion engine, in which short bursts of fuel explosion occur.

In laser thermonuclear fusion, a solid target weighing tenths or hundredths of a gram becomes the source of a micro-explosion equivalent to several tonnes of explosive. Yet this explosion poses no danger either to human health or to the thermonuclear installation itself, because an exceedingly small amount of matter is involved.

In April 1968, at the P.N. Lebedev Physical Institute, a group of scientists led by Nobel Laureate Academician N. Basov succeeded for the first time in obtaining neutrons

from plasma heated by laser radiation.

Thus, another remarkable property of the laser was discovered—its ability to heat matter to the temperature at which the nuclei of deuterium and tritium begin to fuse.

The next stage of research – still incomplete to this day – is devoted to solving a most crucial problem: what is the maximum energy gain that can be achieved through laser thermonuclear fusion?

It seemed that the pulsed method of obtaining thermonuclear energy no longer held any reserves. The plasma lifetime practically did not depend on the design of the installation. The density reserve also appeared to have been fully used. Physicists were already working with “solid” plasma, whose temperature would have made even the Sun envious.

And yet density remained the sole lever which, when pressed, could yield energetically profitable reactions.

A laser beam, striking the surface of a solid target, heats only its surface layer. The high density of the material prevents the light from penetrating to sufficient depth. The enormous thermal energy released at the surface due to strong absorption of the light is carried into the target only by hot electrons.

Such a heating method is not very efficient. By this means one can obtain plasma only with parameters that barely make ends meet. The thermonuclear energy thus obtained will never exceed the energy spent to heat the

material.

In 1972 a group of American scientists proposed a new scheme for laser thermonuclear fusion with an energy gain of hundreds of times thanks to an even greater increase of the target density. Their idea was that a solid pellet of frozen mixture of deuterium and tritium would be irradiated from all sides by laser beams. A layer of hot plasma in the form of a corona should appear on the surface of the sphere. In the overheated and dense "corona" a pressure of up to hundreds of billions of atmospheres should arise and drive the plasma outward (and, of course, toward the center of the sphere).

It is this "press" of fast particles, in theory, that should compress the inner regions of the target, heating them by the work of the compressive forces. The plasma would immediately acquire a density perhaps hundreds of times greater than the density of a solid, and the rate of thermonuclear reactions at such a density would rise sharply: deuterium and tritium nuclei would collide with each other much more frequently.

The first experiments on compressing plasma to ultra-dense states were carried out at the P. N. Lebedev Physical Institute. There, under N. Basov's leadership in 1970, a unique laser installation for spherically symmetric irradiation of a target was created. In a short time, on the order of 10^{-9} seconds, nine laser beams of the facility dumped on a solid pellet 10^{-2} cm in diameter, placed in the center of a vacuum chamber, an energy of 1,000 joules. The light

beams practically simultaneously, to an accuracy of 10^{-10} seconds, converged at one point, creating a plasma and triggering a thermonuclear reaction in it.

The essentially instantaneous process of plasma formation and expansion was analyzed by the scientists with the aid of a motion-picture camera – not an ordinary one, but a laser ultra-high-speed camera with a frame rate up to 1 billion frames per second. Similar thermonuclear installations were put into operation in France and the USA. However, the problem of laser-driven controlled thermonuclear fusion is still far from solved.

In an overcompressed target thermonuclear reactions promise to become energetically profitable if the laser power is increased to 10^5 – 10^6 joules and strict requirements on the shape of the laser pulse are met.

But researchers at FIAN and the Institute of Applied Mathematics of the USSR Academy of Sciences developed a new scheme of thermonuclear fusion. This scheme makes it possible to obtain 1000 times more energy than is expended to create the plasma and at the same time removes the special requirements on the shape of the laser pulse.

The idea consists in compressing with laser beams not solid spheres, as in the previous case, but targets that are thin spherical shells made up of a whole set of layers of light substances, heavy materials, and thermonuclear fuel.

Lasers with simple-shaped pulses and a total power of

one million joules compress the material of the target to a density almost ten times greater than that of the heaviest chemical element. Theoretical estimates indicate that under such conditions thermonuclear fusion reactions would become energetically favourable.

The main task now lies in the advancement of laser technology. Scientists are working on the development of large laser installations that would make it possible to test new physical ideas which could help to solve the problems of controlled laser fusion.

After successful research began in the USA on continuous-operation thermonuclear installations of the Tokamak type, members of the Atomic Energy Commission expressed the view that a demonstration-scale operating thermonuclear reactor would probably be completed by the mid-1990s.

According to American scientists engaged in the field of laser thermonuclear fusion, a demonstration laser thermonuclear reactor will begin operating in about 15 years – that is, also in the 1990s.

Which approach to realising a thermonuclear reactor will ultimately prove the most feasible is still unclear. "...It is still unknown," said L. Artsimovich, "on which branch the golden apple will grow."

At present, research on laser thermonuclear fusion, as well as on continuous nuclear fusion reactions under conditions of prolonged plasma confinement by magnetic

fields, has not yet moved beyond the boundaries of research laboratories. Yet the solution to these complex problems is not far off, especially given the close international collaboration now taking shape.

The agreement between the USSR and the USA, signed in Washington, opens a broad path for such cooperation, mutually beneficial to both sides. It recognises the great importance of addressing the rapidly growing energy needs of the USA, the USSR, and other nations, and provides for joint efforts in the field of controlled thermonuclear fusion.

- But for now, thermal power stations remain the main source of energy; in the coming decades, nuclear reactors will not be able to replace them. Therefore, something concrete must be done today to eliminate their harmful effects on the environment.
- Of course, but the problem is not only pollution. The combustion reaction deprives us of coal, oil, and gas reserves – the Earth's most valuable and irreplaceable organic raw materials – and also of the foundation of our existence: oxygen.
- And will not nuclear and thermonuclear plants pollute the environment as well?
- Nuclear heat is much cleaner in the ecological sense. Radioactive waste can be carefully collected and isolated.
- The “era of fission”, which began with the launch of the first nuclear power plant, will be able to slow down

the development of global atmospheric pollution and conserve gas and oil resources – the most important raw materials for the chemical industry.

Installations that use the fission reaction of uranium nuclei, unfortunately, are not waste-free either. The products of uranium fission contain long-lived radioactive isotopes, the accumulation of which increases in proportion to the rate of development of nuclear energy. By the end of the century, the amount of radioactive waste will have increased several dozen times. However, scientists all over the world are working on a radical solution to the problem of their processing and reliable storage.

The waste products of nuclear energy production are dangerous to humans, but by using special burial methods, it is possible to completely isolate radioactive substances from the external environment.

The design of fission reactors themselves has now been refined so thoroughly that the probability of a person dying from radioactive products in a reactor accident is ten thousand times less than that of being struck by lightning during a thunderstorm.

The "era of synthesis", which will begin with the commissioning of the first industrial thermonuclear reactor and will end with the complete replacement of atomic power stations, will forever free humanity from concerns related to the energy problem. Most importantly, it will

provide truly “clean heat”, unaccompanied by any waste harmful to humans.



In the fusion reaction of deuterium and tritium nuclei, only alpha particles and neutrons are produced, which together carry away 80 percent of the total released energy. Alpha particles are stable nuclei of the chemical element helium and pose no danger. The neutrons must be completely captured within the installation. The plasma will be surrounded on all sides by a material that efficiently

slows down and absorbs neutrons, thereby collecting all the energy produced by the reactor.

In many designs of future thermonuclear installations, the role of neutron absorber is assigned to liquid lithium. Thermonuclear neutrons are effectively slowed down in lithium, increasing its temperature. The flow of molten lithium from the reactor, like molten lava from a volcano, will deliver the nuclear heat to a heat exchanger, where it will transfer it to water.

Lithium nuclei capture neutrons and transform into nuclei of the heaviest isotope of hydrogen – tritium. Tritium is the only radioactive product formed during the transfer of energy in the fusion reaction, but since it is also a participant in this reaction, it is reasonable to reuse it.

American scientists from Oak Ridge have proposed an interesting design of a pulsed thermonuclear reactor in which a mixture of deuterium and tritium is "ignited" by a powerful laser pulse. According to their concept, molten lithium is placed under pressure in a spherical metal vessel up to five metres in diameter and is set into rotational motion. When one quickly stirs tea in a glass with a spoon, a funnel is formed. Similarly, at sufficient rotational speed, a vortex is created in the lithium "liquid", with its bottom located somewhat deeper than the centre of the vessel.

The tablet of frozen deuterium–tritium mixture is dropped into the funnel and "ignited" by a laser at the moment it passes through the centre. The thermonuclear explosion of the pellet, in a thousandth of a second, raises the tem-

perature at the vessel's centre by several hundred degrees. Lithium vapour and the expanding plasma create such a shock wave that it would rip the vessel apart if it reached the walls. But its strength can be greatly reduced by introducing a large number of gas bubbles into the liquid lithium, for example through a perforated ring at the bottom of the vessel. When the shock wave passes through such a bubble, it sprays liquid off the bubble's inner surface. The droplets fly across the bubble and smash against the opposite wall. Most of their kinetic energy is converted into heat. Having passed through lithium saturated with bubbles, the shock wave loses its force and will not harm the installation.

In a thermonuclear container (with radius greater than one metre) filled with liquid lithium, neutron losses will be practically nil. The rotating lithium shell hermetically "seals in" the energy of the micro-explosions, which recur roughly every ten seconds.

Such a thermonuclear reactor poses far less danger to humans and the environment than a uranium reactor. The radioactive nuclei of tritium emit only low-energy beta rays (electrons). Moreover, there is no problem of disposal of this substance. Tritium is required in the very process of energy production, which ensures an almost closed cycle. Only minor leakage of this product may occur, but it can be made negligible and, as scientists believe, even completely prevented, thus avoiding any environmental contamination.

Unlike nuclear reactors, which contain a critical mass of fissile material and therefore require complex safety systems, thermonuclear reactors cannot undergo an uncontrolled nuclear explosion – there is simply not enough fuel for that. Furthermore, in certain fusion reactions – for example, when nuclei of lithium-6 isotopes fuse with protons – only charged particles are produced: the nuclei of helium-3 and helium-4 isotopes.

By collecting these charged secondary particles on electrodes, it becomes possible to achieve the direct conversion of nuclear energy into electricity with an efficiency of up to 90 percent.

For reactors in which both the fuel and the 'ash' consist of stable nuclei, the problem of radioactive contamination simply does not exist. Such reactors could be successfully used for transportation systems.

Apart from generating electricity, thermonuclear reactors may also prove useful for other purposes. A stream of high-temperature plasma from the reactor – a 'thermonuclear torch' – could be employed to decompose matter into atoms followed by their separation. In this way, any waste material could be transformed into raw material useful for production.

The creation of closed, waste-free production cycles will make it possible to avert the threat of an ecological crisis by preventing environmental pollution and preserving natural resources to the greatest extent possible.

Thus, the development of nuclear physics has opened up for humanity the prospect of obtaining energy by a much cleaner method – from uranium and hydrogen, elements not otherwise used in industrial production.

The science of the structure of matter provides a genuine foundation for the future peaceful coexistence and interaction between nature and humankind in all spheres of life.

Our beautiful planet must remain forever blue, no matter how many generations of people succeed one another.

Postface

Damir Mazanav

Since the book was written 1980s, nuclear physics and plasma science have passed through a period of remarkable renewal. Developments in experimental technology, high-speed computation, and international collaboration have deepened our understanding of matter and energy under extreme conditions. From the structure of exotic nuclei to the control of high-temperature plasmas, both fields have moved steadily from theoretical exploration to practical engineering.

In nuclear physics, the discovery of neutron halos in neutron-rich isotopes during the 1990s changed our conception of the atomic nucleus, revealing its delicate, diffuse boundary rather than a sharply confined form. Around the same time, the detection of the top quark and the tau neutrino completed essential confirmations of the Standard Model, while experiments recreating quark-gluon plasma gave humanity its first glimpse of matter as it ex-

isted microseconds after the birth of the universe. The establishment of advanced radioactive ion beam facilities such as RIBF in Japan and FAIR in Germany has made it possible to study the structure and reactions of unstable nuclei with unprecedented precision. Neutrino oscillation experiments at the turn of the century proved that neutrinos possess mass, a discovery that compelled physicists to revise both particle theory and models of cosmic evolution. In applied domains, the twenty-first century has brought new generations of nuclear reactors—compact, modular, and inherently safe—designed to minimise waste and extend the lifespan of nuclear resources. Meanwhile, theoretical models built upon lattice quantum chromodynamics now allow predictions of nuclear forces with exquisite accuracy, linking subatomic interactions to the vast scales of astrophysical processes.

Plasma physics, once the study of a rare and elusive state of matter, has become a cornerstone of modern industry and energy research. The 1980s introduced magnetron sputtering and other controlled plasma methods for producing thin films vital to semiconductor fabrication. The following decades saw the invention of diagnostic tools capable of mapping plasma behaviour in real time, and of feedback systems that allowed precise control of industrial discharges. By the 2000s, atmospheric-pressure plasma jets freed engineers from the constraint of vacuum chambers, expanding applications from microelectronics to textiles. In medicine and agriculture, low-temperature and cold plasma have found use in sterilisation, surface modi-

fication, and food preservation. Today, plasma technology extends to nanoscale treatments, AI-optimised reactors, and the conversion of carbon dioxide into synthetic fuels. At the frontier, the great challenge of controlled fusion continues to unite physics and engineering—ITER, Wendelstein 7-X, and JT-60SA stand as milestones in the long quest for clean and inexhaustible energy.

The instruments built since the late twentieth century have themselves become landmarks of scientific progress. The RI Beam Factory in Japan (2007) delivers radioactive isotope beams of 345 MeV per nucleon at a power of one megawatt, allowing detailed studies of nuclei far from stability. In Germany, FAIR accelerates ions from hydrogen to uranium in pulses of 10^{12} particles, supporting both nuclear and astrophysical research. In Russia, the BN-800 fast reactor and the MBIR multipurpose reactor advance the use of mixed oxide fuels and long-term testing of structural materials. Across Europe, the SPIRAL2 facility produces neutron-rich isotopes up to uranium for nuclear spectroscopy.

In the realm of plasma and fusion, a lineage of devices traces humanity's growing command over high-energy plasmas. The Tokamak Fusion Test Reactor (TFTR) in the United States demonstrated the first full deuterium-tritium operation in 1982, followed by JET in the United Kingdom, which achieved 16 megawatts of fusion power and 69 megajoules of total energy output—records that still guide the ITER project. High-field compact machines such as MIT's Alcator C-Mod and Japan's JT-60SA refined our

understanding of plasma confinement and stability. Germany’s Wendelstein 7-X proved the feasibility of steady-state stellarators, while new superconducting designs such as SPARC in the United States promise compact, high-efficiency reactors for the 2030s.

Taken together, these achievements mark the maturation of two great scientific traditions. Nuclear physics has revealed the subtle architecture of matter and opened paths to new reactor technologies; plasma physics has evolved from a laboratory curiosity into a foundation of modern industry and a beacon for the world’s energy future. As the boundaries between them blur—in high-energy-density physics, fusion diagnostics, and plasma-nuclear materials—the vision of clean and limitless energy, once confined to imagination, now stands within reach of experiment.